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A PRODUCTION PLANNING SYSTEM FOR PLASTIC FOOTWEAR  
IN A SEASONAL MARKET

Doctor of Philosophy  
University of Aston in Birmingham

September 1976

Volume I

## Thesis summary

Modern injection-moulding machinery which produces several pairs of plastic footwear at a time brought increased production planning problems to a factory.

The demand for its footwear is seasonal but the company's manning policy keeps a fairly constant production level thus determining the aggregate stock. Production planning must therefore be done within the limitations of a specified total stock.

The thesis proposes a new production planning system with four sub-systems. These are sales forecasting, resource planning, and two levels of production scheduling: (a) aggregate decisions concerning the 'manufacturing group' (group of products) to be produced in each machine each week, and (b) detailed decisions concerning the products within a manufacturing group to be scheduled into each mould-place.

The detailed scheduling is least dependent on improvements elsewhere so the sub-systems were tackled in reverse order. The thesis concentrates on the production scheduling sub-systems which will provide most of the benefits.

OR  
The aggregate scheduling solution depends principally on the aggregate stocks of each manufacturing group and their division into 'safety stocks' (to prevent shortages) and 'freestocks' (to permit batch production). The problem is too complex for exact solution but a good heuristic solution, which has yet to be implemented, is provided by minimising graphically immediate plus expected future costs.

The detailed problem splits into determining the optimal safety stocks

and batch quantities given the appropriate aggregate stocks. It is found that the optimal safety stocks are proportional to the demand. The ideal batch quantities are based on a modified formula for the Economic Batch Quantity and the product schedule is created week by week using a priority system which schedules to minimise expected future costs. This algorithm performs almost optimally.

The detailed scheduling solution was implemented and achieved the target savings for the whole project in favourable circumstances. Future plans include full implementation.



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## CHAPTER 1 ORIGINS OF THE PROJECT

### 1.1 Introduction

This project concerns the production planning of Injection Moulded Footwear for Dunlop Footwear. The chapter explains how the project arose.

In brief, the Dunlop Company was founded to manufacture pneumatic cycle tyres. As it expanded, it diversified into other rubber products including footwear manufactured by a subsidiary called Dunlop Footwear. Dunlop Footwear progressed well until imported footwear captured a large part of the rubber footwear market. The Company reacted by importing footwear for sale and by mechanising its U.K. production using modern injection moulding machinery. Production planning for this new machinery was complicated. Eventually acceptable scheduling methods, using high stocks, were derived. When it became undesirable to hold such high stocks, the company proposed this project.

### 1.2 Early History of Dunlop Limited

In 1888 John Boyd Dunlop invented and patented the pneumatic cycle tyre. A year later the Pneumatic Tyre and Booths Cycle Agency was founded to manufacture cycle tyres; the company is now called Dunlop Limited after a series of name changes.

The company grew rapidly following spectacular bicycle racing successes on the new tyres. It entered the market for motor-car tyres when restrictions on the motor-car were repealed in 1896 and benefited from the subsequent boom in car sales.

In the early years of this century the supply of raw materials, particularly rubber, was a major concern of the Dunlop Company. To

safeguard this the company purchased rubber estates in Malaya in 1909; in 1916 it opened cotton mills in Lancashire to process the cotton that is used in tyre cords. Dunlop also extended its position as a supplier to the car industry by making wheels and rims to go with its tyres and, later on, other car accessories. At the start of the 1920's Dunlop had a fine reputation due largely to the extensive research and successful design of its products, however, it was almost entirely dependent on the prosperity of the motor-car and bicycle industries.

The company decided to diversify into other rubber-based industries and took over the Charles Macintosh Group. This long established organisation manufactured waterproof "macintoshes" and a wide range of other products, amongst which were rubber footwear made by the Liverpool Rubber Company.

### 1.3 History of Dunlop Footwear

In the early nineteenth century the major materials used to make footwear were leather, fabric and wood. Rubber substituted for leather in some applications, once practical ways of using it were found, because it was waterproof and easy to work with.

The Liverpool Rubber Company was founded in 1859 to make rubber overshoes. It soon diversified into other rubber footwear such as the wellington boot - a calf length waterproof boot, and the plimsoll - a light canvas shoe so called because a rubber sealing strip around the shoe resembled the "Plimsoll Line" on ships. These and related products have been the mainstay of the company since then.

The company was renamed Dunlop Footwear after two take-overs. It acquired its present factory at Walton in Liverpool in 1896. At its peak period in the 1950's it had two other factories. The footwear market then altered for the worse (see 1.4), forcing the company to

rationalise its product range and mechanise its production. It now uses only the Walton factory.

#### 1.4 The Effect of Imports on the Footwear Market

Conventional ways of making footwear have a high labour content. Some categories of footwear require production skills which are easy to develop; in such cases underdeveloped countries, with low wage rates, can produce very cheap footwear.

British tariffs on imported footwear have always been low. Imports of footwear have grown rapidly since consumers have come to accept these products. This is illustrated in diagram 1. Of 164 million pairs of footwear sold in the U.K. in 1950, 7 million were imported. By 1973 there were 76 million imports in a total market of 247 million pairs. Exports by British manufacturers increased slowly and have not exceeded 20 million pairs a year.

Imports are not split evenly between different categories of footwear, (see diagram 2). Skills in leather working are hard to acquire, so imports of leather footwear have grown slowly and still come mainly from developed countries. Canvas footwear has a high labour content and is easy to make overseas, so over 90% of canvas shoes are now imported. Protective footwear with its lower labour content is less profitable to make overseas; with mechanised production methods British manufacturers have retained over half this market, although there are substantial imports of both hand-made and manufactured products.

#### 1.5 Recent Developments at Dunlop Footwear

Dunlop Footwear reacted to the changing market situation, which was particularly serious for canvas products, with a two-pronged solution; to import and to mechanise.



Diagram 1

GROWTH OF IMPORTS IN THE U.K. FOOTWEAR MARKET



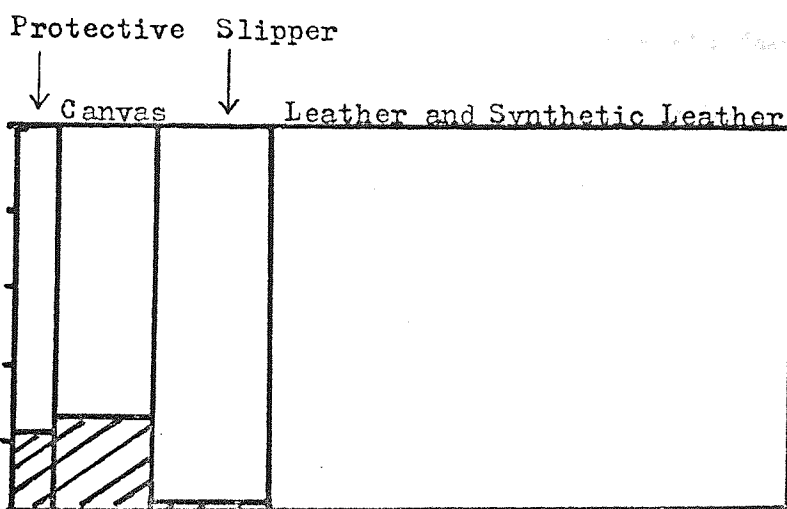
Diagram 2

SALES OF FOOTWEAR IN THE UNITED KINGDOM

1950

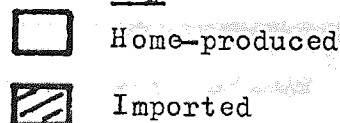
Imports  
as % of  
relevant  
market

Total sales 164 million pairs



Width of each market is proportional to  
share of total sales

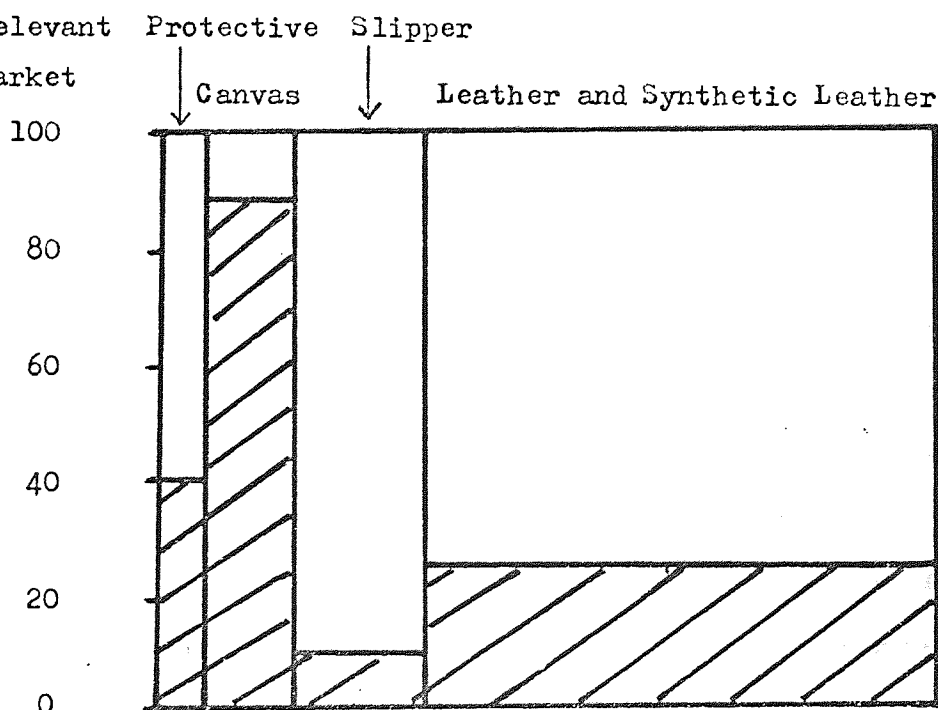
Key



1973

Imports  
as % of  
relevant  
market

Total sales 247 million pairs



It could not compete in price with the imports so the emphasis of the company moved towards marketing. It imported shoes made to Dunlop designs from Hong Kong and elsewhere to sell here.

Footwear production was confined to an expanded site at Walton. The variety of products fell sharply as ranges were standardised and fashion lines were dropped. New production methods using modern machinery replaced labour intensive methods after the acceptability of the new products had been demonstrated.

Two new processes were involved, namely rubber compression moulding and plastic injection moulding. A major advantage of these processes over conventional methods is that, in industrial countries, the saving in labour costs is much greater than the increased capital cost.

Wage rates in some foreign countries are so low that conventional imported footwear is cheaper still, but Dunlop products are competitive when other factors such as quality and service are included.

This project is concerned solely with plastic injection moulding.

Section 1.6 outlines various aspects of this.

## 1.6 Injection Moulding

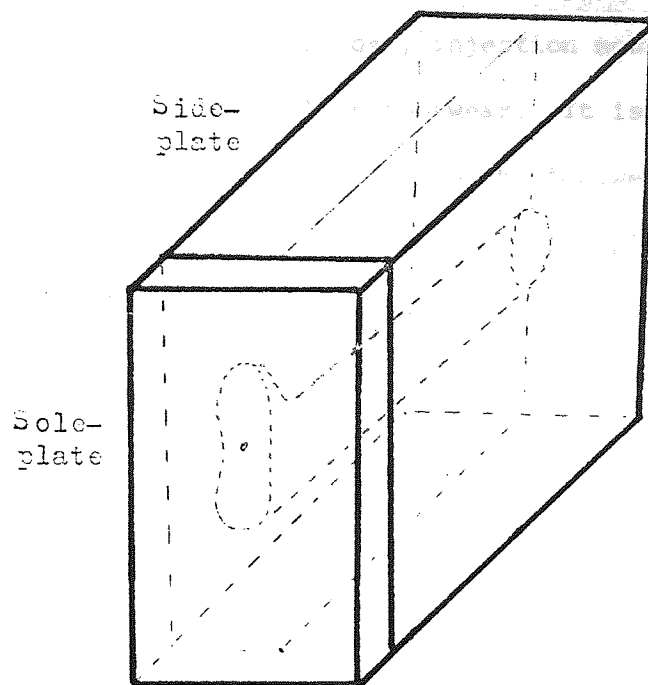
### 1.6.1 Outline of the Process

In Injection Moulding, plastic is squirted or "injected" into a mould where it solidifies in the desired shape. Most plastic footwear, including that made by Dunlop Footwear, is made of polyvinylchloride (abbreviated to P.V.C.) using moulds with four components (see diagram 3).

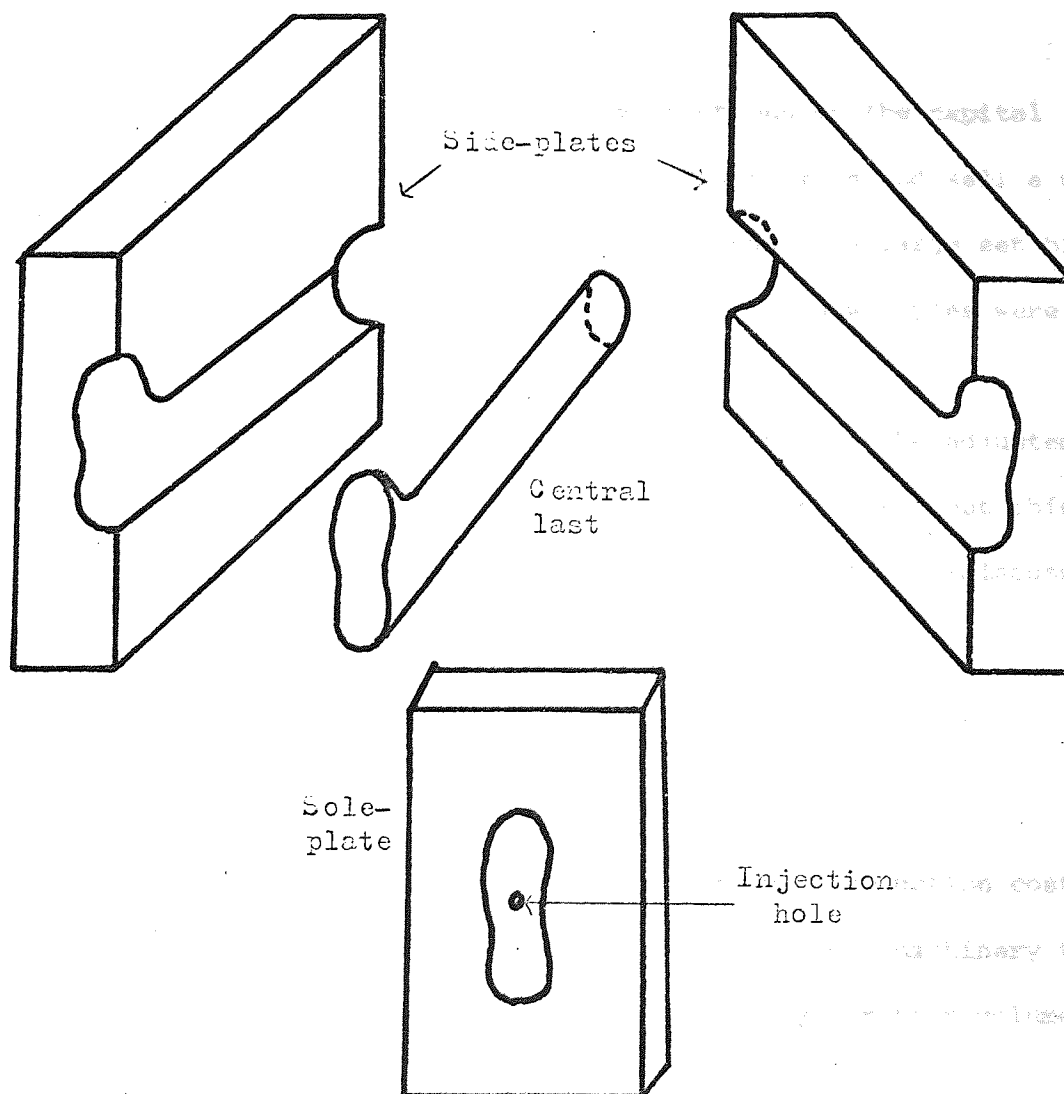
To make a boot or shoe, a cloth lining is pulled onto a central leg-shaped last. The two side-moulds and the sole-plate close around this. Plastic is then injected into the cavity. After a few minutes cooling the completed product can be removed.

Diagram 3

SET OF MOULDS FOR A PROTECTIVE BOOT



Exploded view



### 1.6.2 Advantages of Injection Moulded Footwear

Besides a low labour cost, injection moulded footwear has many advantages over earlier footwear. It is seamless because parts fuse together on moulding, so the footwear is stronger and more waterproof. It is attractive because plastic, unlike rubber, keeps its shape after moulding so complex designs can be reproduced. The particular machinery used at Walton permits two injections into each mould, the first injection forms the leg and the second adds the sole.

This allows the sole to be made from a hard-wearing compound while the leg is soft and flexible. It also enables attractive two-coloured products to be sold.

### 1.6.3 Disadvantages of Injection Moulding

The major disadvantage of injection moulding is the high capital costs of machinery and moulds. Restrictions on the capital employed conflict with marketing desires to make and sell a wide range of fashion products. This would require a large set of moulds which would be replaced frequently as new styles were introduced.

Excess capacity would permit production levels to be adjusted at will for a large investment in spare machinery. Without this there is an awkward production scheduling problem, which is discussed in the next section.

## 1.7 The Production Scheduling Problem

### 1.7.1 Background

Dunlop Footwear resolved the conflict between production costs and marketing potential by purchasing only sufficient machinery to meet anticipated demand, and by buying moulds only for high volume non-

fashion styles.

Since at least one mould is required in each style for each shoe-size to be made, and since there are styles with child's, juvenile's, women's and men's ranges, many moulds are nevertheless required. For production to be economic, the company runs its machines at near capacity throughout the year on three shifts for five days a week. Most styles have highly seasonal sales patterns and there is little opportunity to alter manufacturing seasonally, so there are large seasonal variations in stock levels.

#### 1.7.2 The Problem

Management now had to plan the production for the machines to meet the varying demand within the restrictions of the injection moulding machinery.

A mould only produces footwear which corresponds to it in size and design. The number of distinct moulds is much larger than the number of moulding positions so only a limited range of products can be made at a time.

Mould changes are costly and time-consuming so reasonable quantities should be made in each batch. Therefore stocks must be held to permit batch production as well as acting as a sales cover. The production scheduling problem was, and still is, to determine advance moulding schedules to keep down production costs and satisfy demand.

#### 1.7.3 Initial Investigation

Dunlop's Operational Research team investigated this problem. They reported that it would take two man-years to implement a computer controlled system, and that it was not at present possible to quantify the benefits. They recommended that the problem be given to a university department.



#### 1.7.4 The Existing Solution

Various scheduling techniques were developed over the years with arbitrary constraints imposed to restrict the problem. Initially these methods were fairly effective as there were relatively few brands and high stocks which acted as a production buffer. Recently more brands have been introduced in an attempt to increase the market share, and there has been pressure to reduce stocks because of a worsening economic climate. The existing techniques were not designed to operate in this environment so the problem returned, and more sophisticated methods of solution became necessary.

Dunlop Head Office had just become involved in a new scheme at Aston University which linked project work in industry with postgraduate work at the university. Dunlop Footwear still could not afford to employ an Operational Research team on this problem; it was therefore proposed for a possible project at Aston.

#### 1.8 The Interdisciplinary Higher Degree Scheme

Aston University was a College of Advanced Technology before it obtained its charter in 1966. It had good industrial links which the University Grants Committee and the Science Research Council were keen to strengthen. A failing of conventional Ph.D research courses was the unsuitability of many postgraduates for work in industry. The U.G.C. agreed to help finance a postgraduate scheme at Aston to do research in co-operation with industry. This promised to provide employees with postgraduates who had industrial experience. To succeed it meant that the industrial desire for a practical solution must be reconciled with the academic desire for an analytical solution.

Once support was available, Aston University established the

Interdisciplinary Higher Degree Scheme (I.H.D.). It lobbied firms and public service organisations for suitable projects.

The criteria sought were that the problem should be soluble within three years, but not so urgent that this time span was excessive; that it involved several academic disciplines; that it had a sufficiently academic basis to be suitable for a Ph.D thesis; and that a solution would be of value to the organisation.

If a suitable problem was found and the organisation concerned was willing to sponsor a student on the scheme, the department would seek a student acceptable to all parties involved who was willing to undertake the project.

#### 1.9 Terms of Reference for the Project

The production scheduling problem at Dunlop Footwear was proposed as a suitable project. It satisfied the criteria since its likely time span and value to the company were acceptable, and the solution was thought likely to involve mathematics and plastic processing, and to generate new academic ideas.

The Dunlop Footwear management were only interested in the specific production scheduling problem, but the University felt that this was too restricted. They proposed that the project should involve associated areas, such as sales forecasting, which come under the general title of production planning. The management agreed to these wider terms of reference with the proviso that they did not intend to implement suggestions in other areas for several years.

The terms of reference for this project were, in order of importance:-

- A. To design, and if accepted by management, implement a production scheduling system integrated with existing systems for the products made in the Injection Moulded Footwear Department such that there is an optimum balance between -

1. Loss of sales due to stock shortage
2. Capital investment in stocks
3. Production efficiency

B. To determine the effects of further capital investment in machinery and moulds.

C. To investigate sales forecasting, and to consider how the proposed systems could be extended to include this.

This thesis describes the work done on the project which has kept reasonably closely to these terms of reference. The emphasis of the work reflects the management proviso.

2.1    Introduction

This chapter describes the environment of the production planning system being investigated; this is shown in diagram 4.

A major input to production scheduling is the demand. Shoe retailers' and wholesalers' buying policies are outlined in section 2.2 and the firm's product range is described in section 2.3.

The other major input for production planning is the record of stocks of finished goods held in the warehouse. These need no explanation, except to note that up-to-date values are held on the company's computer.

Section 2.4 describes the injection moulding machinery and introduces some limitations it imposes on production planning. Section 2.5 describes the production process for injection moulded products.

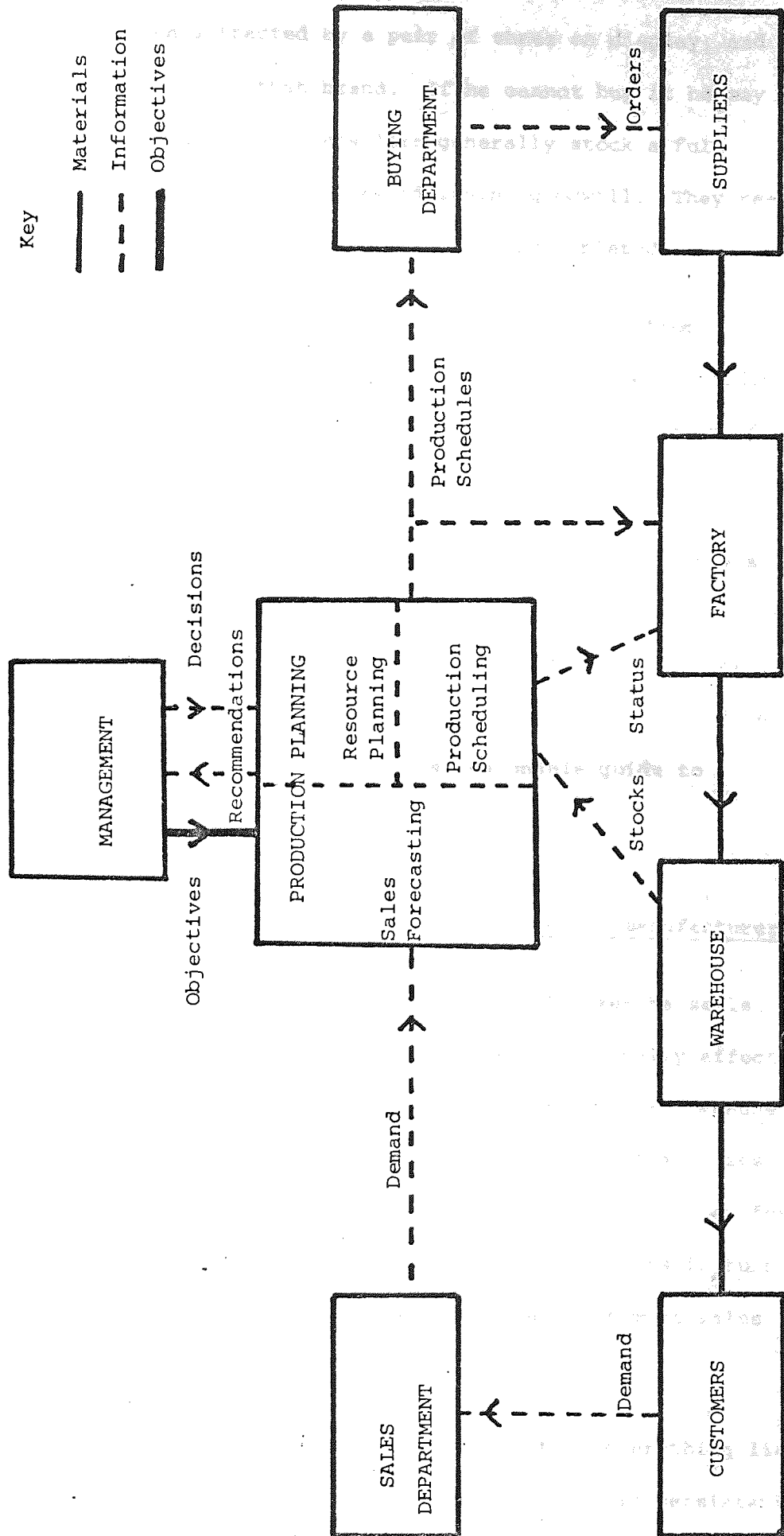
Section 2.6 divides production planning into three stages and describes the requirements of each stage. The objectives of production planning are discussed in chapter 3. They are here assumed to be to meet demand and minimise costs. Section 2.7 gives a sub-division of the problem which is justified in chapter 5. Finally section 2.8 outlines the contents of the thesis by chapter.

2.2    The footwear market - customers' buying policies

Most footwear sold in Britain passes through a chain from the manufacturer or importer to a wholesaler, and thence to a retailer before reaching the customer. In contrast, Mail Order Houses acting as wholesalers sell directly to the customer.

Diagram 4

THE PRODUCTION PLANNING ENVIRONMENT



A customer is often attracted by a pair of shoes on display, and asks for his own size in that brand. If he cannot buy it he may well change his retailer, so retailers generally stock a full range in the brands they sell to avoid losing goodwill. They re-order from their wholesaler as their stocks are depleted.

The demand off a manufacturer is the sum of all orders from individual wholesalers. Retailers and wholesalers order according to their future expectations. Thus the total orders for a brand are unpredictable, although retail sales may be uniform.

Since customer buying patterns alter slowly, the split of orders between sizes within one brand remains reasonably constant. It is called the 'sizeroll' and is measured in sales of each size per thousand pairs of that brand sold. When a new style is introduced the 'sizeroll' of a similar product is a reasonable guide to future sales.

#### 2.2.1 Effect of customers' buying policies on the manufacturer

It is important for a manufacturer to stock all sizes he sells. A sustained shortage of a particular size will eventually affect the retailers. As explained above, goodwill can be lost because of a shortage and the loss can be substantial for central sizes in the range, so retailers will often cancel a complete order for one style rather than be short of one size. Wholesalers in turn act similarly so a stockout of a vital size can halt most sales of a style.

Mail Order Houses are even more concerned to stock everything listed in their catalogue. They may well change suppliers if persistently



undersupplied on vital sizes.

To prevent stockouts of some sizes and overstocking of others it is desirable for the manufacturer to determine the sizeroll and produce in accordance with it. This is particularly important for seasonal products if a substantial stock is built up before the selling season.

The 'saleable' or 'balanced' stock at any time is defined as the lowest ratio of the stock of any size to its sizeroll. The remaining 'unbalanced' stock, the total stock minus the saleable stock, is virtually unsaleable except in times of general shortage until further supplies of the critical size(s) are produced. Since this is generally within a couple of weeks, substantial unbalanced stocks should cause no concern providing sufficient balanced stocks are available to meet immediate demand.

### 2.3 The firm's product range

The firm sells specialised footwear formerly made partly of rubber. This includes slippers, canvas shoes and rainproof footwear such as wellingtons.

The styles listed in table 1 are now made from plastic by injection moulding. There are two major categories shown in this table with further subdivisions related to the machinery and explained in 2.4. The term 'shoes' refers to canvas footwear, while 'boots' refers to protective footwear such as wellington boots.

Table 2 presents the terminology about the product range used in production planning. (See also 2.4). Other notation is given in the glossary.

Table 1

<u>Style</u>	<u>Colours</u>	<u>Brands</u>	<u>Sizes per Brand</u>	<u>Machine Type</u>	<u>Mfg. Group</u>
<u>Canvas Shoes</u>					
Casual	1	5	10	Canvas	1
Basic Sports	2	3	20	"	2
Tennis	1	2	15	"	3
Hockey	1	1	7	"	4
<u>Protective Boots</u>					
Bright Wellingtons	1	4	15	Large Protective	1
Dull "	1	3	7	"	1
Coloured "	3	3	10	"	2
Industrial "	1	1	7	"	3
Fashion "	4	4	7	"	4
Short "	2	3	7	Medium	1
Infants "	5	5	7	Small	1
Golf Shoes	3	3	7	"	2

### 2.3.1 Seasonality of the demand

Many of the firms products have specialised uses with a limited selling season. 'Protectives' are sold mainly in the autumn for sale to the public in the winter. The seasons of all the protective products are similar. Over 40% of the year's sales (to wholesalers, etc.) occur in the autumn quarter and less than 10% in the spring. (See diagram 5).

There is more variation in the seasons of the different styles of canvas shoes. Some styles are designed for summer sports such as tennis, while other styles are mainly for school children. The former styles have their peak sales in the spring, the latter in the summer. Thus canvas shoes as a whole have a longer season than the protectives, although each style is nearly as seasonal as the protective boots.

## 2.4 Injection moulding at Dunlop Footwear

### 2.4.1 Design of the machinery

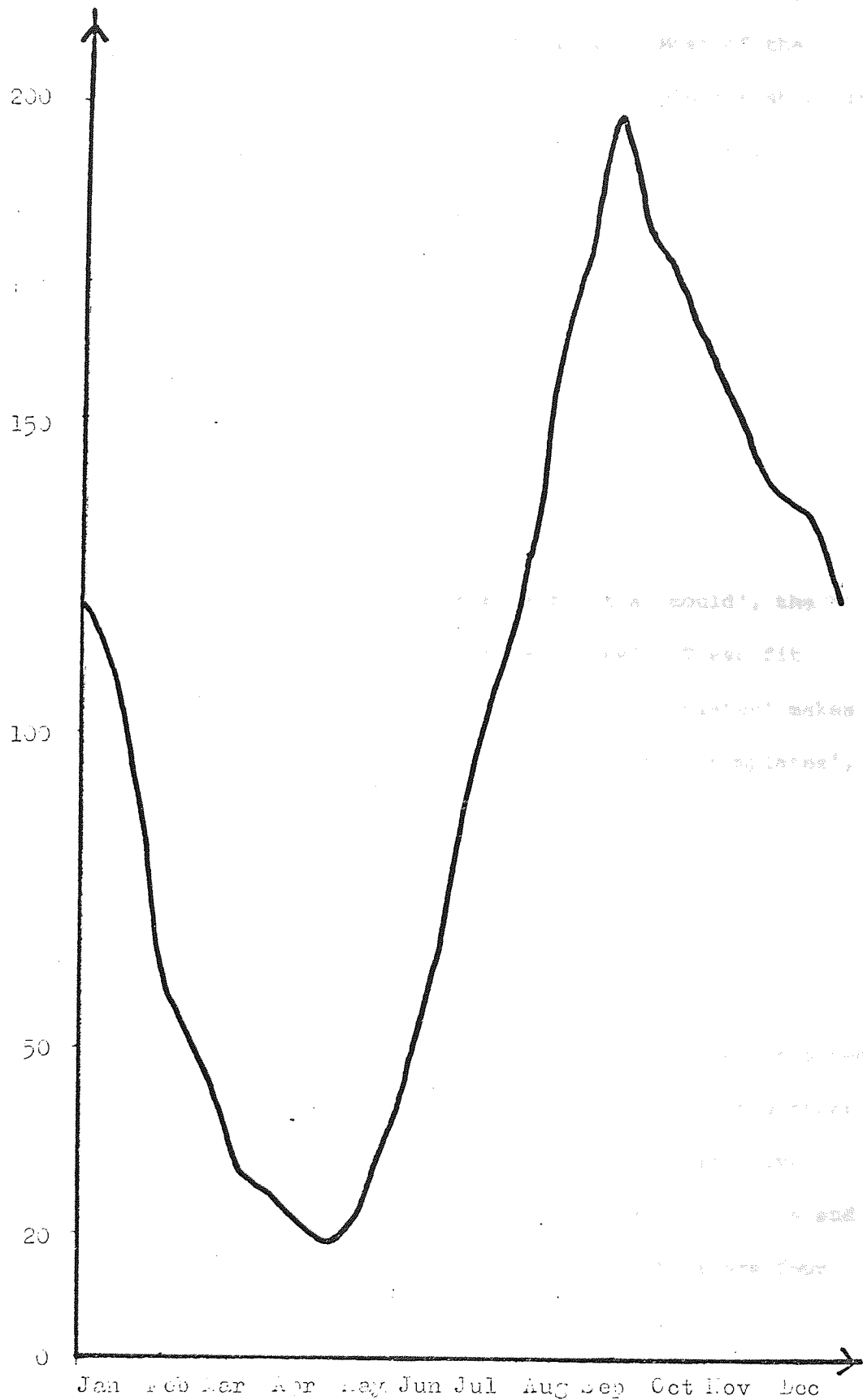
Most injection moulding machines have one injection barrel and one mould. The plastic is heated and mixed in the injection barrel by the injection screw. It is then injected into the mould. The barrel refills while the moulding cools. For small mouldings, little time is wasted for either activity. However, for large mouldings, such as footwear, the cooling time is disproportionately long and the barrel would be idle most of the time.

In injection moulding machines for the footwear industry, the injection barrel is used more efficiently by serving several moulds. The moulds are placed around a turntable, which by rotation

Diagram 5

THE SEASONALITY OF A TYPICAL PROTECTIVE BOOT

% of average  
weekly sales



presents each mould in turn for an injection of plastic (see diagram 6).

Chapter 8 explains the operation of the machinery in detail; for the present it is sufficient to know the above. Most of the machines used by the firm have two injection barrels (as shown in the diagram), but this has no effect on production planning.

#### 2.4.2 Note on terminology

In the footwear industry, the basic planning unit is a pair of shoes or boots. The left and right-footed moulds necessary for production will always be used together; therefore, in the rest of this thesis the term 'mould' is reserved for the set of mould pieces used to produce a pair of footwear.

Where it is necessary to refer to the parts of a 'mould', the individual metal parts are referred to as 'dies'. These fit together to make a 'template'. Thus a pair of 'templates' makes a 'mould'. Similarly a 'mould-place' will hold two 'templates', that is one 'mould'.

#### 2.4.3 The machinery at Dunlop Footwear

There are nine machines in the Injection Moulding Department. Each of these holds five 'moulds' giving 45 mould-places to schedule each week. Three of these machines make canvas shoes, the other six make protective boots. There are three sizes of 'protective' machines; small, medium and large, with four large machines and one each of the other two sizes. Thus, in all, there are four machine types.

REPRESENTATION OF AN INJECTION MOULDING

MACHINE FOR PROTECTIVE FOOTWEAR

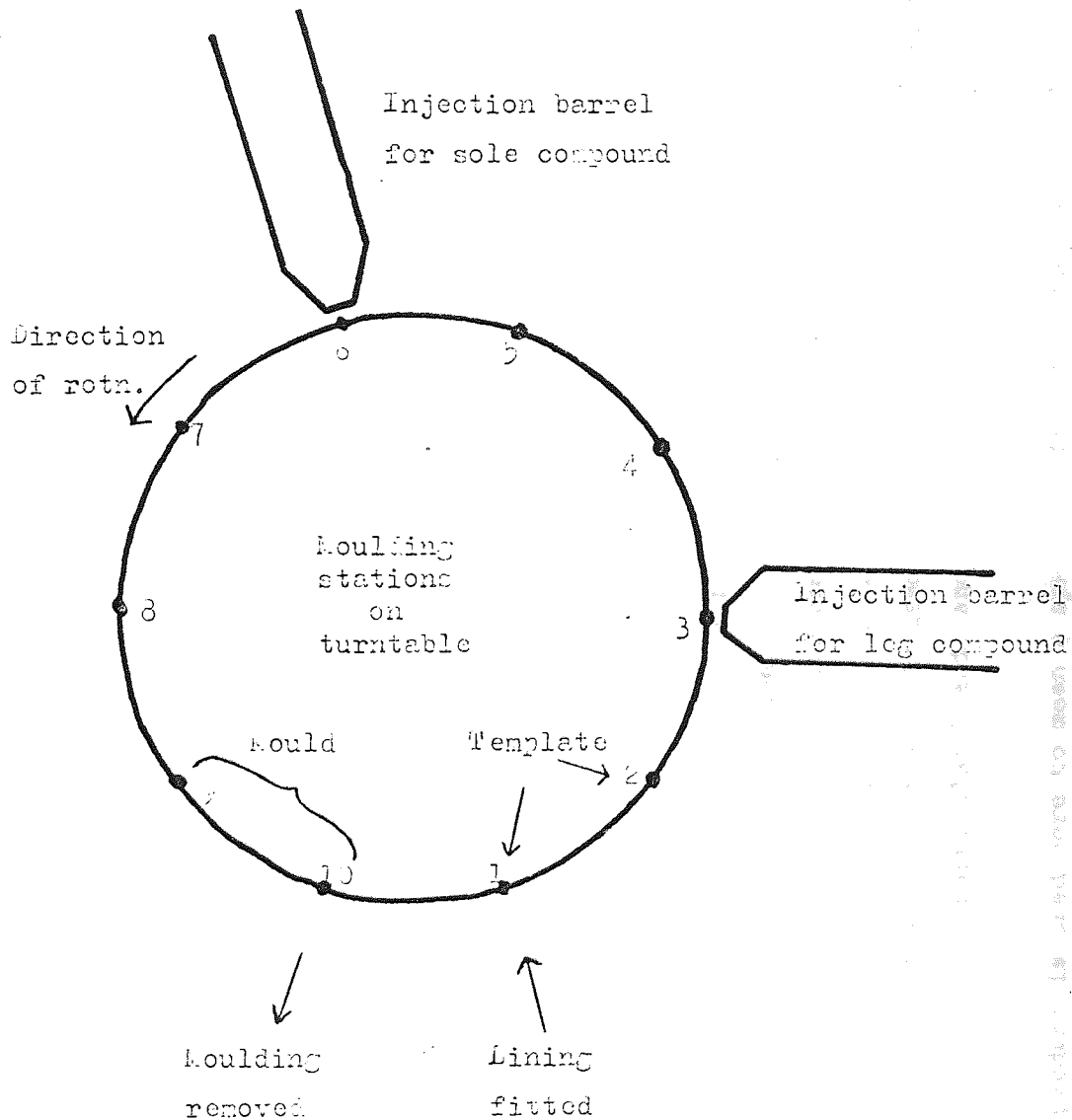




Table 2 Planning Hierarchies

Sales Terminology

<u>Term</u>	<u>Meaning</u>	<u>Example</u>
Class	Either canvas shoes or protective boots	Protective
Sales group	Related styles	Bright Wellington
Style	All brands of same basic form, differing in colour	" " - Black
Brand List No.	All sizes in a particular colour and style	7170
Size range	Childs, Juveniles, Womens or Mens	Juveniles
Size, Product	A specified shoe size of a particular brand	" Size 11, Brand 7170

Production Terminology

<u>Term</u>	<u>Meaning</u>	<u>Example</u>
Class	Either canvas shoes or protective boots	Protective
Machine type	Type of machine used	Large
Mfg. Group	Set of products using compatible moulds	Bright and dull Wellingtons
Colour	All products of same colour, can be made together	Black
Mould	Identifies the mould used	Bright Juveniles 11
Brand, Product	The particular brand, and hence product, to be made	7170 Size J11

NOTE: The term product is used here to mean a specific size of a specific brand.  
This is the lowest planning level.

#### 2.4.4 Manufacturing groups (see tables 1 & 2)

Each product can only be made on machines of one particular type. Further restrictions apply because not all products can be moulded together.

All the footwear coming from one machine at one time will have the same colour(s). Different products can be obtained from a mould by varying the injection colour (or colours, but it is sufficient to consider only one). Not all of the possible combinations are sold. For example, some moulds only make black products, others never make them; these moulds can never be together in a machine.

Moulds which can be in use together are called 'compatible'.

Compatible moulds are generally compatible for all colours made by either mould. The set of products made from a compatible set of moulds is called a 'manufacturing group'. At any time a machine can only be producing products of one manufacturing group and one particular colour.

In the few cases where different styles of product use moulds which are only compatible on some colours, one style is required in quantity, the other rarely, so that it is convenient for planning purposes to consider them separately. Such styles have therefore been given separate manufacturing groups.

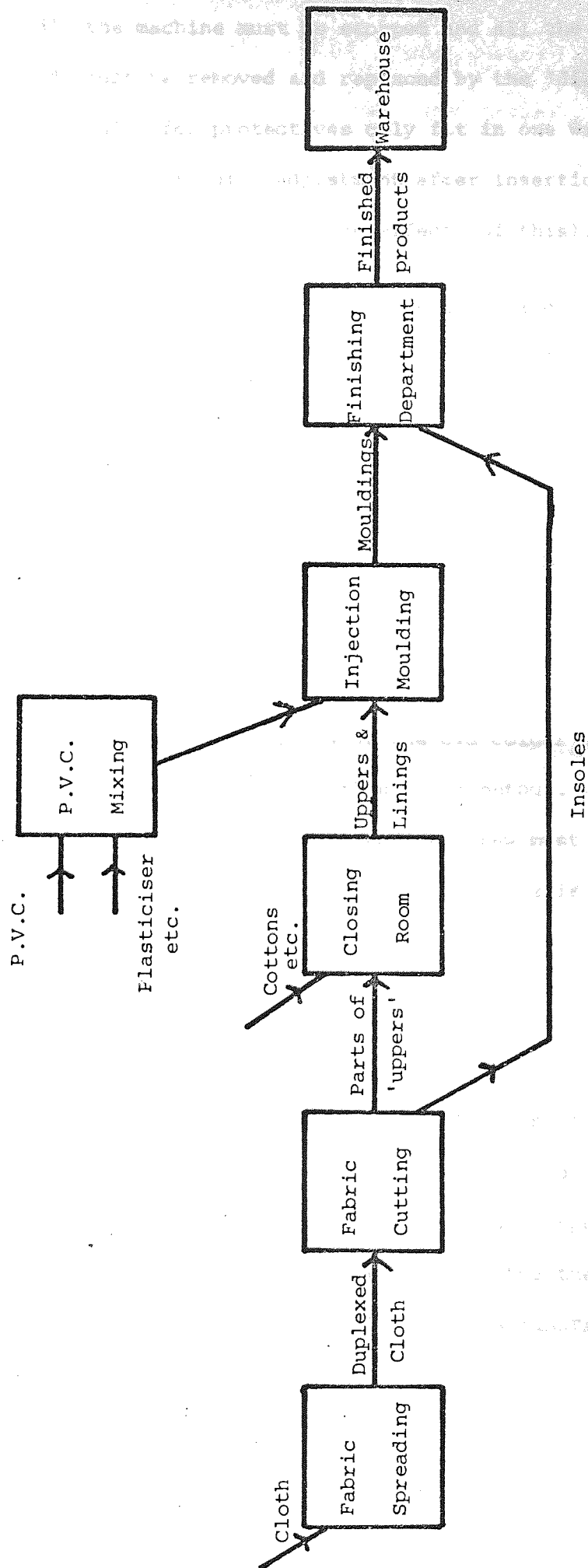
#### 2.4.5 Moulds and mould changing

Each 'mould' makes only one size of footwear. By varying the lining or 'upper' used, several distinct brands may be made from it. This may require a slight adjustment to the sole plate, but the cost and time required are negligible.

Diagram 7

MAJOR PRODUCTION DEPARTMENTS AND MATERIAL FLOWS

FOR INJECTION-MOULDED PRODUCTS



To change a 'mould', the machine must be stopped and all the 'dies' from the old 'mould' must be removed and replaced by the 'dies' for the new mould. The moulds for protectives only fit in one way, but the moulds for canvas shoes require adjustment after insertion to obtain satisfactory output (see 8.5 for the effects of this).

In either case mould changes are costly and time-consuming. It is therefore desirable to minimise mould changing by making large batches of each size, changing the brand as appropriate.

#### 2.4.6 Colour changes

The colour of P.V.C. output from an injection barrel can be changed to a darker colour merely by 'flushing' the barrel, that is by running through the new colour until it is clear.

When changing to a lighter colour, traces of the old colour remain in the barrel for a long time. This discolours the output. The barrel must therefore be opened and the injection screw must be thoroughly cleaned before running a lighter colour. This is called a 'screw clean'.

#### 2.5 The manufacturing process

The factory is organised into departments with specific functions. 'Supply' departments process the raw materials, ready for moulding in the 'moulding' departments; the products are trimmed, inspected and packed in the 'finishing' departments. Diagram 7 shows the departments and the major material flows involved in the manufacture of injection moulded footwear.

### 2.5.1 Construction of the products

Protective boots consist of a thin sock-like lining entirely surrounded by P.V.C. Canvas shoes also have a lining, which is stronger and made of canvas. This is called an 'upper' because it forms the upper part of the shoe; only the sole, toecap and surround are made of P.V.C.

### 2.5.2 Processing

#### 2.5.2.1 The plastic

The plastic is prepared in the moulding department by adding various liquids to P.V.C. powder. The major additives are plasticisers to prevent decomposition on heating. These are thoroughly mixed and granules of pigment and possibly regranulated P.V.C. are added to give a 'dry blend' powder ready for immediate use.

#### 2.5.2.2 Canvas uppers

The 'upper' starts as two rolls of cloth. A cheap backing cloth and a higher quality facing cloth are 'duplexed', that is joined together with a layer of latex, in the Fabric *mechanical* Spreading section.

In the Fabric Cutting room, various shaped parts are stamped out from several layers of cloth by steel dies. Sufficient parts to make twenty pairs of 'uppers' are boxed together and sent to the Closing Room.

Before the cloth was cut, it could have been used to make any size of any brand requiring that cloth; once cut, the brand

and size to be moulded has been determined.

The 'uppers' are sewn together into a limp shoe-shape in the Closing Room. The room contains about fifty machinists each with their own specific tasks. As the boxes of linings are processed, they proceed from one machinist to another via a controller.

At first the pieces are sewn flat, but, once the back is sewn up, the upper is doughnut shaped and special sewing machines are used. The uppers are completed by the addition of binding and steel eyelets for lacing with, finally, a fabric insole sewn on the bottom.

#### 2.5.2.3 Protective linings

Some 'protective' linings are bought in ready made, the rest are made in the Closing Room. Fabric tube is knitted and guillotined into thirty inch lengths. These are cut diagonally at one end and sewn up to form a rough knee-length sock.

#### 2.5.3 Moulding

Shoes and boots are moulded on different injection moulding machines using individually sized moulds. A 'template' (which is half a 'mould') consists of a central last onto which the lining is pulled, side-moulds and a sole plate. The latter close around the last leaving a cavity around the lining, into which P.V.C. is injected. The dies open after a few minutes cooling and the moulded product can be removed for 'finishing'.



#### 2.5.4 Finishing

The moulded products are examined for any defects, such as the lining showing through or surface flaws. Top quality products are called 'bests'. Those with minor defects are classified as 'seconds', any others are rejected.

Excess P.V.C., which was injected to avoid incomplete mouldings, is now trimmed off. An insole is inserted into some products and all shoes are laced. After this minor processing, most products are packed into cartons and despatched.

A few brands require special 'finishing'. This can be to ensure a higher quality, or for extra processing as on Golf Shoes, which have a tongue attached and binding sewn around the edges. It takes much longer to finish these brands and a backlog of work may build up so that it is inadvisable to make more than one such 'awkward' brand at a time.

#### 2.6 Production planning

The firm makes its profit by selling footwear to customers. The role of production planning is to ensure that the correct footwear is available for sale.

The detailed objectives of production planning are discussed in chapter 3. It is sufficient here to assume that they are to meet demand and to minimise costs.

Production planning involves forecasting the future demand; determining and requesting the necessary resources, and scheduling the production to meet this demand. I call these stages sales

forecasting, resource planning and production scheduling.

The preceding sections of this chapter have discussed the production planning environment which was presented in diagram 4. The remainder of the chapter discusses production planning itself in the three stages defined above.

#### 2.6.1 Sales forecasting

The firm needs advance planning to enable it to employ its labour and capital resources profitably and to satisfy its customers. Few customers order in advance except in times of general shortage; plans must therefore be made using forecasts of future demand. What forms of forecast are needed?

Production planning (as defined here) does not include the long term when the nature of the business may alter. It covers from short-term scheduling to planning for at least a year ahead. The range of styles sold in this period will be similar to the current range and any additions will be known already.

Current quantitative forecasts are based on comparable recent sales modified by subjective information. Because sales are seasonal with very low off-season sales, recent sales provide little information until late in the season and forecasts rely largely on the previous year's demand. This makes forecasting for new brands extremely difficult in the first season.

Planning over a year ahead needs only aggregate demand estimates to identify how the labour force should alter and whether new machinery is required, so forecasts by sales groups, which correspond to the type of machine used, are sufficient. Since the future is uncertain

planning can be more flexible if the range of likely demand is specified rather than a single estimate.

To identify the requirements for each category of skilled labour and to order some raw materials, forecasts at manufacturing group or brand level for up to six months ahead are desirable, but need only a moderate accuracy. Forecasts for the rest of the season will also show whether maximum production is now desirable for brands with a limited production rate.

Finally, detailed forecasts by size and brand are required for production scheduling. Each schedule covers four months ahead, but with re-scheduling every four to six weeks, the schedule is only firm for the first two months. Any forecasting errors over this period will lead to corresponding variations in the stocks.

Fortunately, forecasts are normally more reliable when stocks are low because most of the commitments for the coming month are already known. Accurate forecasts are required for the following month; thereafter accuracy is less important except for brands only made occasionally. Such brands need reliable forecasts for the period until the following production batch is started.

#### 2.6.2. Resource planning

The firm has physical, human and monetary resources such as machinery, raw materials, skilled and unskilled labour and cash. All are required to produce footwear. The resource planning problem is to procure sufficient resources to meet likely demand in the medium term (from three to eighteen months ahead).

The machinery is operated all the week with maintenance at weekends

(see 1.7.1), so there is little opportunity to increase production by overtime. Adjustments to the labour force are therefore used to control the production rate. There are two major areas of resource planning. These are to determine if any new investment is required, and to fix the labour force levels for each category of skilled and unskilled labour. These decisions will depend on the monetary resources which are assumed known and fixed.

Knowing the production rates for each operation and similar facts, the resources required to meet any future demand can be determined. A forecast of the range of likely future demand will show what resources may be required.

Management actions will depend on the currently available resources and the desirability of changing these. Where current resources may be insufficient, management must decide whether to acquire more or to risk stockouts. This could lead, for example, to further investment in machinery or to retraining operatives because the requirements have altered.

If resources are excessive, management must decide whether to use them all and build up stocks, to leave some idle or, in the case of excess labour, to make some redundancies.

### 2.6.3 Production scheduling

I distinguish here between planning, which is determining the resources required to meet a given set of requirements, and scheduling which is deciding how best to use the available resources. In production scheduling a fixed labour force and machinery is assumed with pre-determined production rates.

#### 2.6.3.1 Scheduling constraints

The fabric cutting and closing rooms are flexible. They are seldom restricted by the capacity of any machine. They can fulfil any work load which requires a reasonably balanced contribution from each type of machinist. The production rate of most brands could be doubled without harm, providing the total effort required remains constant. A few brands have exceptional requirements of some operation; these have limited maximum production rates unless the manning is altered. The finishing department is also flexible although, as mentioned earlier, there are some combinations of brands which it is desirable to avoid.

The running costs for these departments depend on the work to be done but not significantly on the order in which it is done. Scheduling can therefore be done with little concern about these departments providing some simple constraints are observed. These are seldom binding for long.

The injection moulding department is the only department imposing significant constraints. Its major constraints are that each machine can only produce products of one 'manufacturing group' and one colour at a time and that its production rate cannot easily be increased. Some lesser constraints are introduced in chapter 8.

Most raw materials are used regularly and are always on order, others can be ordered at short notice. Some materials with long lead times must be ordered well in advance as part of the resource planning. The availability of these materials constrains

feasible schedules.

In summary, to schedule the factory satisfactorily it is sufficient to consider only the injection moulding department and a few constraints external to it. Only in this department do the running costs depend significantly on the schedule (since mould changes are costly), therefore an optimal schedule for it should be near optimal for the factory.

#### 2.6.3.2 Scheduling the injection moulding department

A production schedule for the injection moulding department will specify:-

The moulds to be in each machine at any time;  
the colour(s) of P.V.C. to inject;  
and the brand to make from each mould.

Since moulds from different manufacturing groups cannot be together in one machine, it is difficult to schedule directly and more convenient to schedule in two stages. The first stage defines which manufacturing group and colour each machine is to make at any time. This is a form of aggregate scheduling and generates a manufacturing group schedule or 'machine loading'.

The second stage determines the particular brands and sizes, with associated moulds, to produce from each machine subject to the machine loading. This is called 'product scheduling'.

Since mould and colour changes are costly and time-consuming, the machine and mould loading are altered only when necessary. It is convenient to plan in discrete periods during which no alterations occur. In some cases daily plans are made, but a



weekly unit is generally short enough and has the advantage that changes occur at the weekend as is usually preferable (see 8.5).

#### 2.6.3.3 Scheduling other factory departments

Other factory departments process the available work so they can be planned from the schedule for the Injection Moulding department, basically by moving this schedule forwards or backwards in time. For example, it is safe to allow a processing time of one week for a canvas 'upper' in the Fabric Cutting department and two weeks in the Closing Room, thus the current cutting 'ticket' should be related to the moulding programme three or more weeks ahead. It would be possible to include a few items in this ticket to be moulded a fortnight hence, and to expedite these through.

#### 2.6.3.4 Buying

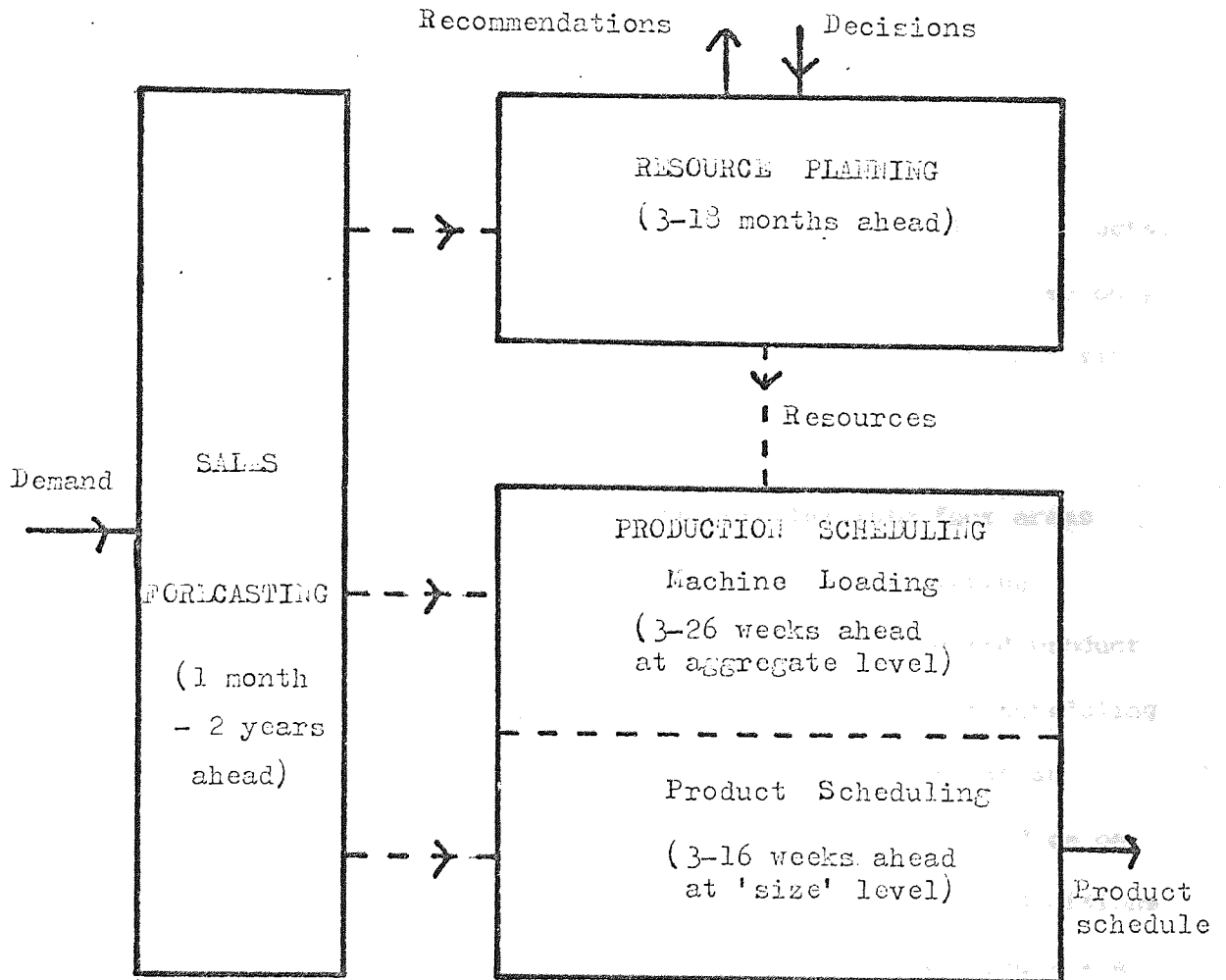
The buyers order many items used regularly, such as cloth, laces and P.V.C. powder, by following standard stock-control criteria. They use the schedule to order special items such as linings which are individually sized. The delivery date requested will depend on the uncertainty in delivery and the processing required before moulding.

#### 2.6.4 Summary

Production planning splits into three areas; sales forecasting, resource planning and production scheduling. Sales forecasting projects the future situation with less detail further in the future. Resource planning determines the need for and effect of new investment or changes in the labour force. Production

Diagram 8

THE PRODUCTION PLANNING SYSTEM



scheduling determines the planned output from the factory.

The injection moulding department is the only awkward production department so that it is sufficient to schedule other departments from this one.

There are two natural stages in scheduling this department - machine loading and product scheduling - corresponding to aggregate and detailed levels of scheduling.

## 2.7 Subdivision of the problem

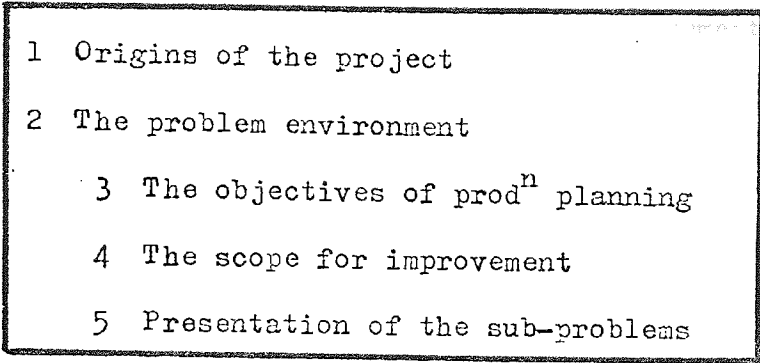
My project concerns production planning for injection moulded products. My terms of reference emphasise production scheduling and give me only advisory powers of forecasting and resource planning. This emphasis is reflected in the work I have done.

Diagram 8 shows how I have sub-divided the problem into four areas using the natural subdivision identified earlier and splitting production scheduling into two sections - machine loading and product scheduling. (Note carefully the difference between product scheduling and production scheduling.) Machine loading is scheduling at an aggregate level determining which manufacturing groups to produce on each machine, while product scheduling involves the detailed decisions on the brand and size to make from each mould. These two stages are separated because the problem of overall optimisation is too large, but they are closely related and the relationship between the stages is investigated later in this thesis.

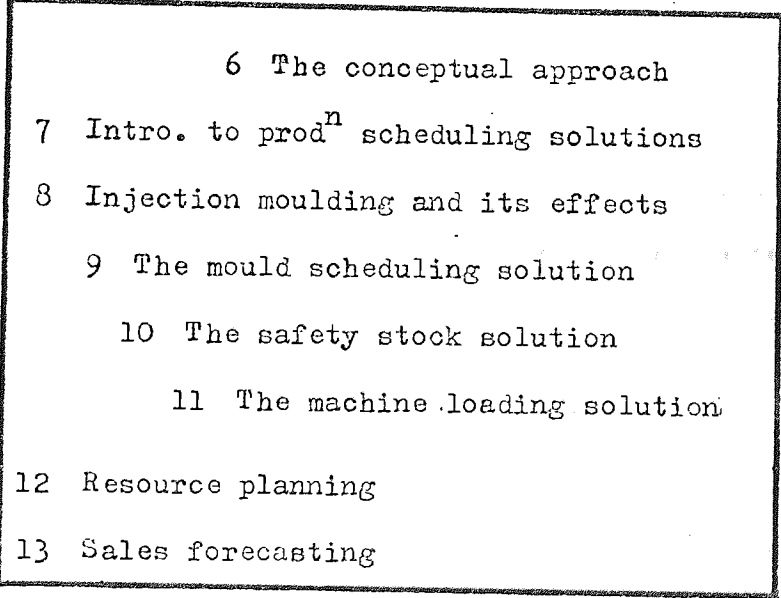
## 2.8 Outline of the thesis (see diagram 9)

The thesis is divided into three parts each containing several chapters. The first part introduces the problem. It commenced in

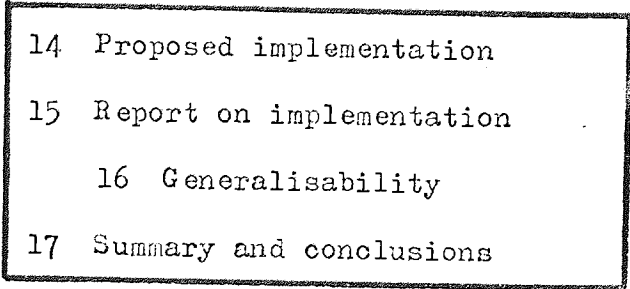
DEFINITION OF PROBLEM

- 
- 1 Origins of the project
  - 2 The problem environment
  - 3 The objectives of prod<sup>n</sup> planning
  - 4 The scope for improvement
  - 5 Presentation of the sub-problems

ANALYSES

- 
- 6 The conceptual approach
  - 7 Intro. to prod<sup>n</sup> scheduling solutions
  - 8 Injection moulding and its effects
  - 9 The mould scheduling solution
  - 10 The safety stock solution
  - 11 The machine loading solution
  - 12 Resource planning
  - 13 Sales forecasting

SYNTHESIS

- 
- 14 Proposed implementation
  - 15 Report on implementation
  - 16 Generalisability
  - 17 Summary and conclusions

chapter 1 with an account of the origins of the project; this chapter describes the problem environment; and chapter 3 discusses the objectives of production planning. Chapter 4 shows that the project had sufficient scope for improvement to be worthwhile. Chapter 5 completes the introduction by subdividing the problem and specifying the objectives and constraints for each sub-problem (or module).

The second part of the thesis produces the scheduling solutions and shows why the proposed solutions are expected to give nearly optimal results. Chapter 6 stresses that the emphasis has been placed on obtaining workable solutions. Chapter 7 introduces the scheduling solutions; chapter 8 considers the effects of the Injection Moulding process on the problem and its solutions. Chapters 9 to 13 produce and justify the proposed solutions to the various modules into which the problem was divided. In particular chapters 9 and 10 concern the detailed product scheduling and chapter 11 explains how the results from there are aggregated for the machine loading.

The final part of the thesis draws the project together again. It commences with details of the proposed and actual implementation in chapters 14 and 15 respectively. The latter chapter shows that the project was indeed worthwhile. Chapter 16 shows where the solution can be applied more widely. Finally the conclusions are stated in chapter 17.

## CHAPTER 3    THE OBJECTIVES OF PRODUCTION PLANNING

### 3.1    Introduction

A production planning system is part of a larger system, the company. To be an effective component of this system its objectives must be compatible with the company's objectives.

This chapter identifies features required in the design of a production system. It deduces these by considering the possible objectives of production planning. These objectives in turn depend on the company objectives.

The chapter thus starts with company objectives and proceeds to production planning objectives. It deduces a general design for a production planning system and then checks that this is suitable for Dunlop Footwear.

### 3.2    Objectives of a firm

'The firm is an economically or 'money' motivated social organisation. This implies that a set of objectives or purposes can be identified in most firms, either in explicit form as a part of the firm's business plan, or implicitly through past history and individual motivations of key personnel.' (1)

Basic references for the following discussion on objectives are Ansoff (1), Horowitz (2) and Cyert and March (3).

#### 3.2.1    Profit maximisation

Classical economics prescribes that the objective of a firm is to maximise its profits. The microeconomic theory of the firm

shows that, in a perfectly competitive stable market, there is an equilibrium level for production, price, etc. At this level no firms are making excess profits and any firms not operating at this level will be making insufficient profit. Therefore, to survive, a firm must seek to maximise its profits (2), (4).

In stable conditions, the optimum short and long term strategies are the same. In the current uncertain and changing conditions there is unlikely to be a strategy which is best for all time-scales and circumstances. One strategy may be preferable to another with a higher expected profit because it is less risky, or because it gives a larger immediate profit.

Profit maximising is still generally accepted as an objective, but to select an optimal strategy additional objectives must be specified. Since there is no 'correct' solution the approaches have proliferated. Most are equivalent under classical assumptions to profit maximising.

Many approaches cater for the choice between profits now and later by aggregating these into one term. Typical objectives are to maximise the expected discounted profit (5) or the return on investment (6). The latter objective may be appropriate if the available capital is limited.

The above approaches ignore risk and work with the expected profit. A substantial theory of risk analysis has been developed to explain how choices between risky alternatives are made (7).

The distinction between these approaches is only significant for strategic decisions. For tactical decisions, as in this project, they are similar. I have selected maximising the expected discounted



profit as my profit maximising objective.

### 3.2.2 Survival of the firm

Rothschild (8) and Drucker (9) proposed that a firm's major concern was not to maximise its profits but to ensure its survival. Drucker has five survival objectives which amount to maintaining the human organisation, adapting to circumstances and ensuring adequate profitability.

These objectives are necessary for survival but do not dictate the firm's strategies. Secondary objectives, including profit maximisation, have been proposed to determine the strategies. Baumol (10) and Galbraith (11) suggest that many firms aim to maximise sales growth. This has many potential advantages for the managers including improved status, higher salaries and a sense of security.

### 3.2.3 Objectives of key personnel

The key decisions in an organisation are made by people at several levels of the organisation. Each has his own personal objectives. Traditionally it was assumed that these objectives were subjugated to the organisation objectives so that it acted as a united whole; this is no longer assumed.

By considering the objectives of relevant individuals, Cyert and March (3) assert that "most organisational objectives take the form of an aspiration level rather than an imperative to maximise or minimise". Objectives tend to be stated relatively, and may well be contradictory but, at any time, only certain objectives are given prominence.

In a similar vein, Simon (12) proposes that organisations are satisfied with strategies which meet their constraints. They generate their strategies from certain 'generator' constraints and accept them if they meet the other constraints. Decisions are made independently and are unlikely to be optimal with respect to overall goals.

### 3.3 The researcher's objectives

What should a researcher take as his objectives? His client is the company for which he works, but he may have responsibilities to particular individuals in this company.

Ackoff (13) argues that the company, and hence a researcher in it, should be responsible to all its 'stakeholders', such as employees, customers, investors and the public. He proposes that 'the principal objective of a corporation should be to maximise the rate of growth of corporately produced net social consumption'.

I believe that the researcher's main responsibility is to the company but that he has a secondary responsibility to all stakeholders. In particular any proposals he makes must improve the overall performance of the company to be valuable, and should be acceptable to those involved to encourage implementation. My approach to this problem is explained in more detail in chapter 6.

### 3.4 Production planning objectives

A production planning system, as defined in Chapter 2, combines resource planning, which sets the labour force levels and controls the acquisition of production facilities, with production scheduling which determines the output from the factory and hence the stock levels.

It has no control over such variables as wages, selling prices and advertising policy, which are environmental variables for it. In particular, demand is independent of production planning except when it is adversely affected by a shortage of stock.

This section shows that production scheduling objectives vary little with most common company objectives, but that resource planning objectives depend critically on these.

#### 3.4.1 Company objective - profit maximisation

The profits calculated for any period depend on the accounting methods adopted. Over a long enough period, using any acceptable method, the profits indicated should be similar.

I am valuing stock at the current marginal cost of production and spreading capital costs over the life of the machinery. This attributes the profits to the time of sale. The profit in any period, ignoring factors unconnected with production planning, is the gross profit on sales minus the production planning costs, the storage costs and the capital costs.

The cross profit on sales is the revenue minus the marginal costs of production. The production planning costs include costs for changing the labour force or the machine settings, expediting costs, and also costs of running the system. The storage costs include interest on the value of capital tied-up less the increase in stock value if marginal production costs rise.

##### 3.4.1.1 Resource planning to maximise profit

To maximise profit, the resource planning objective is to select the strategy for resource acquisition which maximises the

expected discounted profit as defined above.

On this basis, new investment should be made if it shows an expected profit however small. By comparison, if the company objective were to maximise the return on investment, new investment should be made only if it shows a greater return on investment than that currently obtained.

The labour force should be altered to the value which maximises the expected profit. The current levels are only relevant if there is a cost for changing the labour force.

Similar comments apply to other resources. In general the optimum level of a resource can be found as the point at which its marginal value equals its marginal cost.

#### 3.4.1.2 Production Scheduling to maximise profit

Production scheduling is done with a fixed set of resources so that the decisions are to set the product mix and sequence. If capacity is limited so that whatever is produced is sold, then the immediate profit is maximised by the product mix which maximises profit.

In general, over a long period, demand is limiting since the company will expand to satisfy demand. Sales of most products contribute towards the company objectives so that it is worthwhile to meet all the demand for these. Unprofitable products may arise as by-products but will not be expressly planned if maximising profit is the objective. Such products are ignored in the rest of this section; with this proviso, the first objective of production scheduling is to satisfy all the demand

for its products.

The capital costs are fixed because the resources are known. If the demand is known, the gross profit on sales is fixed; the only variable terms would then be the production and storage costs.

In fact the demand may be reduced as the result of a stockout. If this effect is known the resulting loss of future profit can be charged against the stockout. This gives the second production scheduling objective - to minimise the sum of production, storage and stockout costs.

### 3.4.2 Company objective - survival

#### 3.4.2.1 Resource planning to survive

If the company's main aim is to survive then its resource planning decisions will be conservative and biased against potential risk. New investment will not be made unless its expected return substantially exceeds its cost.

Without strong reasons for changing the work force, no action is likely to be taken. When changes are made they are likely to be large and late. However, if survival is sought through sales growth with low selling prices, new investment may be made even if it is unprofitable.

This is particularly likely where individuals hold strong personal objectives. For example a sales manager may exaggerate potential sales to ensure new machinery is purchased.

#### 3.4.2.2 Production scheduling to survive

The first production scheduling objective given earlier, 'to satisfy all the demand for its products', will certainly be held

by a firm seeking survival. It is likely to be particularly concerned about its major customers. To retain their custom it may give them priority treatment unjustified by its profits from them, and may even continue unprofitable lines.

Such treatment of major customers will give the actions that a profit maximising firm would take in these cases if it had high stockout costs for these customers.

There is no survival advantage in high production or storage costs, so a firm seeking survival will try to minimise the sum of production, storage and implicit stockout costs.

### 3.4.3 Effects of personal objectives on production planning

#### 3.4.3.1 Resource planning objectives of key personnel

The resource planning objectives for profit maximisation and for survival are dissimilar but not excessively so. Major differences appear when individual motivations are considered.

Many parts of the company are involved in resource planning so decisions are ratified at several levels. To assist their cases, people may bias information in their own favour.

For example, new investment brings prestige to those closely concerned; it can be justified by optimistic forecasts. Investment decisions are made at a high level without detailed knowledge of the circumstances; as such they will favour the most optimistic forecasts.

As another example, a manager may increase his labour force to increase his power; alternatively he may not reduce it because he

is afraid of the union leader concerned.

#### 3.4.3.2 Production scheduling objectives of key personnel

The variety of personal objectives is wide enough to justify almost any resource planning decision. By contrast, few people are involved in production scheduling and they have little to gain from it.

A scheduler is generally judged on stockouts, production costs and stocks by comparison with previous performance. He will therefore aim for a satisfactory performance, but not the best, since he then could not improve. His emphasis on each of the above areas will depend on the implicit values of his supervisor.

#### 3.4.4 The responsibility of production planning to stakeholders

If the firm is responsible to its stakeholders (see 3.3) it should be reluctant to decrease its labour force, and its investment decisions should consider many matters irrelevant to profit.

It is still desirable to satisfy all demand; manufacturing unprofitable items may serve the public good. Other production scheduling decisions are unlikely to be affected.

#### 3.4.5 Conclusions on production planning objectives

New investment decisions are generally based on the expected profit from the investment. The criteria for selecting suitable investments vary from firm to firm; and the actual performances will seldom reach expectation.

Most other resource planning decisions, including setting labour



force levels, are, in theory, designed to maximise the firm's profit. In practice these decisions result from a complex set of interactions between several groups of people and are only loosely related to profit maximising.

Production scheduling involves few people. Its aim is usually to satisfy the demand for the set of active products which may exclude unprofitable items. It also aims to keep the production, storage and stockout costs satisfactorily low.

### 3.5. The design of a production planning system

#### 3.5.1 Resource planning

Resource planning decisions made objectively by a self-contained production planning system would not automatically be implemented since they interact with other management decisions of a political or subjective nature.

It is therefore realistic to consider the resource planning function as advisory. It need not then be complete since external factors can be considered when making the final decisions.

The alternatives are generally known and small in number, so it is sufficient for the system to be able to present the monetary effects of any proposed decision on investment or employment levels for the expected future conditions or any other conditions.

This can reasonably be provided by a model of the system, with the solution produced by analyses or, more probably, by simulation.

#### 3.5.2 Production scheduling

Production scheduling, unlike resource planning, can be done

objectively with relatively little interference. It is therefore desirable to design the system to be as complete as possible so that it can be left alone.

If the objective of the system is to minimise 'costs', then, by suitably defining these costs, it will be applicable under most company objectives. The design will therefore be flexible.

Since many routine decisions are involved in production scheduling it may be desirable to use a computer. This allows many calculations to be made but slightly reduces the flexibility of the system.

### 3.6 Dunlop's production planning objectives

Dunlop Footwear does not exactly fit any of these patterns. Its senior management purport to aim for profit maximisation and major decisions must be justified on profit grounds. Each division is expected to make a profit; it presents its strategy in a 'Management Plan' and its objective is to follow this strategy even if circumstances alter. There are no policy guidelines for decisions not considered in this plan.

Many key day-to-day decisions are made by junior managers who have no explicit objectives to implement. They act in their own interests which include satisfying their own managers. Their decisions are sufficiently consistent to deduce certain implicit production planning objectives; these are more related to survival than to profit maximising.

#### 3.6.1 Resource planning decisions

To restrict the capital employed, new investment is limited. Capital is allocated to projects in decreasing order of return on capital. Investment proposals must therefore be accompanied by a forecast of

the likely return on capital.

The employment policy is to maintain a stable labour force and in particular to avoid seasonal recruitment and layoffs. To improve labour relations, changes in employment levels are only made when they are clearly necessary.

It is therefore pointless to calculate the ideal labour force by sophisticated methods. A model of the system, as proposed in 3.5, could however be helpful in decision making.

### 3.6.2 Production scheduling objectives

The company wishes to make an adequate profit but is concerned about its security. It favours its major customers more than is justified on considerations of long term profit.

There are various categories of customer. The implicit management policy is to give preferential treatment to priority customers particularly during a stock shortage. There is no policy to maintain a better supply of certain brands, for example the most profitable.

One could therefore compute a stockout cost function for each brand. It would depend on the shortfall and the proportion of the demand arising from favoured customers, but not on the brand itself. Brands which are no longer profitable are only made in exceptional circumstances, such as to balance up the stock of a clearance line.

### 3.6.3 Production planning guidelines for Dunlop Footwear

Dunlop Footwear's objectives are comparable with those identified earlier in this chapter. I therefore follow the guidelines proposed in section 3.5 on the design of a production planning system.

In particular, since my terms of reference stress production scheduling, the production scheduling modules will aim to be directly applicable with little manual intervention, while the resource planning module will be small and advisory.

## CHAPTER 4      THE SCOPE FOR IMPROVEMENT

### 4.1    Introduction

The project was set up to improve the production planning system. It will only be worthwhile if there is sufficient scope for improvement to justify the time and effort required to achieve it. I therefore investigated the original planning system to see how it worked. In so doing, I gained sufficient understanding of the system to be able to estimate the optimum mould scheduling performance.

I determined the scope for improvement by seeing how well the production scheduling in 1972 could have performed. After making allowances for the likely failings of a new scheduling system, I concluded that an adequate saving of £8,000 per year should be possible.

This chapter provides the story behind this. Sections 4.2 and 4.3 describe the original system, Section 4.4 gives some performance measures, and finally, Section 4.5 covers the feasibility study.

### 4.2    The Management Plan

The Management Plan states the company's policy for the next few years. It is prepared in the autumn and gives detailed plans for the coming year. The sales and production budgets are relevant to production planning. They are prepared interactively following the principles below.

#### 4.2.1    The sales budget

Annual sales targets are determined at sales group level by the appropriate sales manager. Historic sales information is available,

but he need not use it. His targets may be adjusted by senior managers, but the reasons for any adjustment are not recorded.

The Market Research department uses historic sales information to divide the target sales between brands. The past seasonality is used to generate monthly targets.

#### 4.2.2 The production budget

Current plans are used to project the stocks at the end of this year by sales group; target levels for the following year-end are a specified number of weeks' sales. The desired production is the sales target plus the change in stocks. By combining all sales groups made on one type of machine, the machine utilisation is obtained.

A further addition gives the labour force required; since this can only take discrete values it is unlikely the sales targets and manning policy are compatible. Sometimes the sales targets are altered, and sometimes the plan includes an alteration of the work force during the year. In the latter case, the decision is reconsidered shortly before the change is due to prevent unnecessary hiring and firing.

The planning manager prepares a monthly machine loading. This states the quantity of each manufacturing group (closely related to the sales groups) to produce each month. It aims to provide an adequate sales cover throughout the year.

He first schedules short runs of the low demand brands which form their own manufacturing groups. The rest of the loading is prepared by intelligent consideration of the constraints. Once a suitable



plan is found, no attempt is made to improve it.

The plan is revised twice in the year. These revisions are an improvement both because they use recent information, and because they use sales forecasts rather than sales targets. However, the revisions are still not systematic, and the forecasts are fairly poor (See 13.4).

#### 4.2.3 Suitability of the Management Plan

The Management Plan is principally a costing and policy document. It is used as a planning tool since nothing else is available. It is not very suitable since the assumptions behind it are not presented, the sales figures are targets rather than forecasts, and no indication of the likely errors is given.

### 4.3 Production scheduling

#### 4.3.1 Machine loading

The planning manager keeps graphs of the cumulative sales for each major manufacturing group. These graphs give little information early in the year, but it is then out of season for all brands, so planning is not critical and the production budget given in the Management Plan is followed.

Later in the year, the planning manager estimates the annual sales by projecting the recent trend. If these figures differ by less than about 25% from the current sales budget he accepts the current production budget. Otherwise he informs the appropriate sales manager about the discrepancy in forecasts and they jointly revise the production plan. If they cannot agree, the 'Management Committee', which includes all senior managers, settles the plan.



The production budget states the quantity of each manufacturing group, in machine-weeks, to produce each month. This determines most of the machine loading. The precise machines to use and weeks for manufacture are chosen on an ad-hoc basis, to give a feasible machine loading.

#### 4.3.2 Product scheduling

The scheduling horizon is set about four months ahead. Product scheduling for each manufacturing group is performed in the following stages.

1. Estimate the total production for the manufacturing group over the scheduling period. Add the current stocks to get the gross availability.
2. Set the requirements for each size and brand equal to the commitments on the sales order file due by the scheduling horizon. This trial setting is adjusted at stage 4.
3. Determine the number of days or weeks to produce each colour to give a similar sales cover for each brand. Settle the production dates for each colour.
4. Adjust the requirements for each colour to equal the gross availability. If excessive, take only the most immediate commitments. If insufficient, increase the requirements for each brand in proportion to the expected demand. The extra requirements are split between the sizes according to the 'sizeroll' of the brand.
5. Accumulate the net requirements, the total requirements minus current stock, for each size over all brands to get the requirements for each mould. Divide by the production per mould per week to give the number of weeks for which each mould is needed. Appropriate rounding ensures that the total equals the number of

available mould-weeks.

6. Produce a mould schedule

(a) For minor manufacturing groups made in short-runs.

The object is to minimise the number of mould changes. Each mould needs at most one mould change for each colour. If more than one mould is needed to meet the requirements of one size, keep one mould in continuously. Group together moulds for which the requirements equal the output from a mould-place while making one colour; and schedule these in turn into a suitable mould place. (Note that the brand to make is automatically determined by the injection colour.)

(b) For major manufacturing groups made in long-runs.

Rescheduling is done a few weeks before the expiry of the old schedule. The rest of this schedule is generally retained unless any unscheduled products are urgently needed.

About half the requirements for moulds corresponding to sizes with low sales covers are scheduled early on; the other half is scheduled near the end of the period. The full requirements for other moulds are scheduled in one batch in mid-period.

The dates are adjusted so that five moulds are scheduled for each machine each week and the number of mould changes at any weekend is acceptable to the fitters.

It is desirable to restrict the range of sizes scheduled together in one machine (see 8.3). If several machines are available, the small sizes are allocated to one machine, the middle sizes to another, etc. This yields several smaller unconstrained scheduling problems.

If only one machine is available, a narrow range of sizes is scheduled each week. This range roams up and down the size ranges over the scheduling period. Characteristically, such a schedule resembles a snake (see Diagram 10).

7. Given the mould schedule, the brand(s) to make from each mould in any week are determined by the relative urgency of each brand for this size. Over the period the production of any size and brand will equal the net requirements to within a week's production.

This completes the product scheduling. The schedule is used to calculate raw material needs and to schedule the various factory departments. If a mould cracks, or there is a major machine breakdown, simple and obvious adjustments are made to the schedule.

#### 4.4 Performance measures

##### 4.4.1 Existing measures

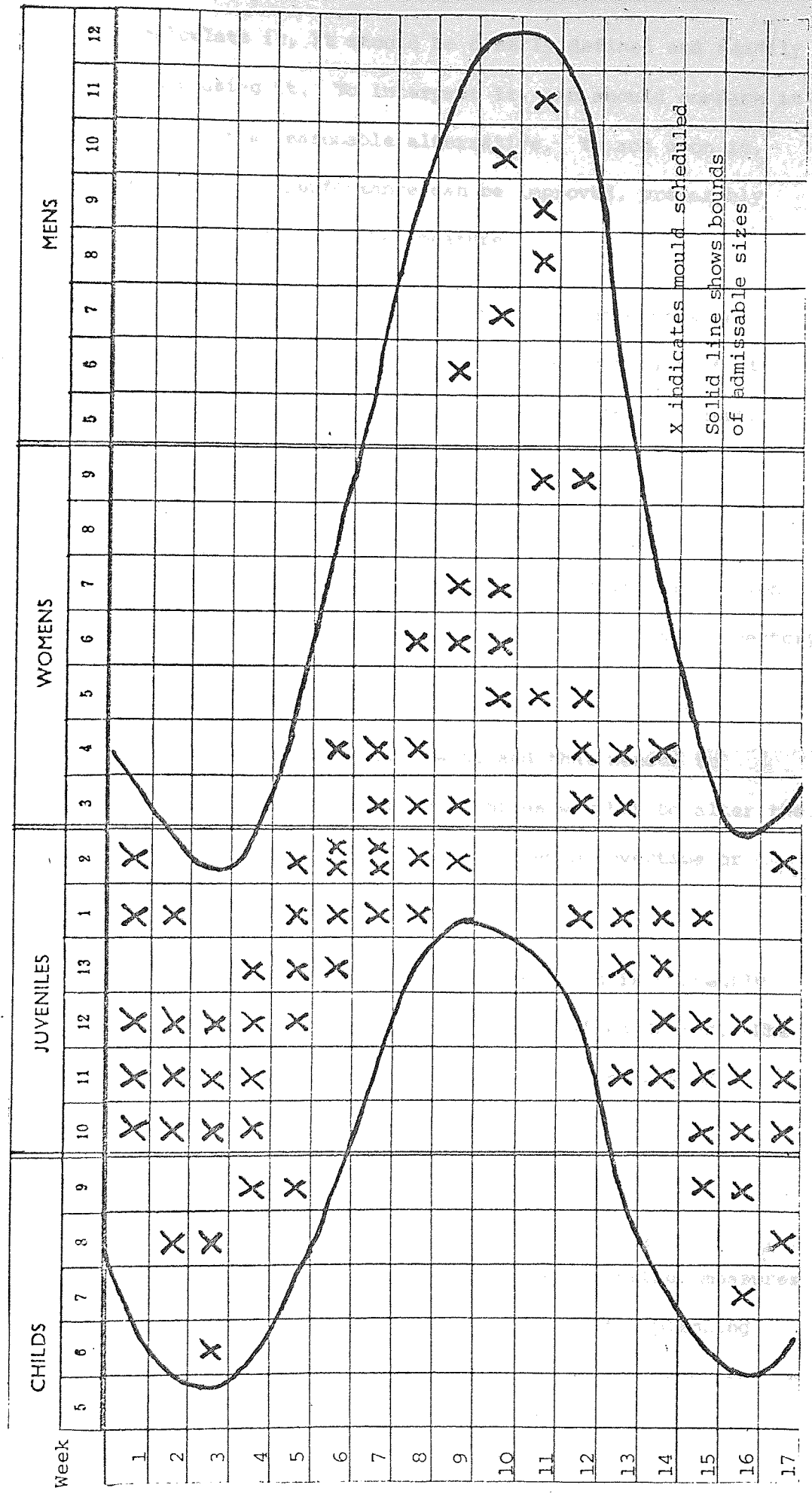
How can the performance of the production planning system be measured? Its output is a set of schedules which control production from the factory, and therefore affect production costs, inventories, and unsatisfied demand.

The company measures these three variables as part of the accounting system. On their own they are poor measures of the performance of the production planning system since the results depend largely on the initial situation and since no standards are available. As a result, a good performance in difficult times may be considered worse than a poor performance in easy times.

A measure should be calculated, interpreted and acted upon if

Diagram 10

A MOULD SCHEDULE SHOWING 'SNAKE-LIKE' BEHAVIOUR



necessary. To calculate it, it should be clearly defined and readily understood by those using it. To interpret it, one should compare it with either a target or a reasonable alternative. To act upon it, one wishes to know how the performance can be improved, preferably without adversely affecting any other measure.

The above three measures are easily calculated, but no consistent targets are available and any simple action is likely to affect at least two of these measures, one of them adversely. This suggests that compound measures may be appropriate.

The company uses compound measures of the stocks and demand to determine its policy. It has no joint measures involving production costs since it does not know how these should vary with, say, inventory.

Its fourth measure is the difference between the projected stock at the end of the season when stocks are lowest and that needed to satisfy customer demand. This measure determines whether to alter the production rate. For example, output is increased by overtime or recruitment if projected stocks are insufficient.

Its fifth measure is the percentage of the stock which is currently saleable. The higher this is, the lower the unsatisfied demand. The sales department desires to maximise this measure regardless of resulting increases in production costs.

#### 4.4.2 New performance measures

Since the above five measures do not suffice, several further measures were devised. These evaluate the performance of specific planning subsystems (see 2.6). There are no resource planning measures because labour force levels, etc., are principally set outside the planning system.



#### 4.4.2.1 The forecasting performance

Two measures of forecasting performance are used. These are the ratio of the mean forecasting error for each brand to the mean error

- a) using last year's actual sales as a forecast of this year's sales and
- b) using a forecast obtained by exponential smoothing (a simple forecasting technique (see 13.4)).

The forecast used should be at least as good as these two forecasts, therefore these ratios should normally be below one. The forecasting method should be changed if the values are persistently above one.

#### 4.4.2.2 Production scheduling performance

The measure of excess production scheduling costs is the excess of actual production, storage and shortage costs for a machine type over the minimum costs (as calculated in chapter 11) for the current stock level expressed as a percentage of minimum costs.

This measure is a combined measure of the effectiveness of all the production scheduling modules. The measures given below indicate the product scheduling performance. There is no separate measure here of the machine loading performance but further measures are introduced later.

#### 4.4.2.3 Product scheduling performance

The product scheduling module is divided into two further (sub-) modules. The details are given in chapter 5.

The 'mould scheduling' module aims to minimise production costs for

a given 'freestock' - stock available for reducing such costs (see 5.5). Its performance measure is the excess of actual production costs for a manufacturing group over the minimum cost for that freestock expressed as a percentage of the minimum cost.

The 'safety stock' module aims to minimise shortage costs for a given 'balanced stock' - stock available for preventing shortages (see 5.5). Its performance measure is similarly the excess of actual shortage costs over their minimum for that balanced stock expressed as a percentage of the minimum cost.

#### 4.5 Feasibility study

Shortly after starting this project, I made a feasibility study on it by comparing the potential and actual performance in 1972. This involved constructing alternative machine loading schedules for the year, and estimating the potential improvements in customer service under an ideal planning system.

##### 4.5.1 Actual performance

The actual performance in 1972 was typical of the current system. There were high stocks of protectives, and a sustained stockout for one brand of canvas shoes, while other shoes remained in good supply. The production costs were moderate, but required large stocks.

It was reasonable to expect improvements in all areas of production planning. Although each year is different, 1972 seemed a representative year, so this study was expected to reveal the value of the project.

##### 4.5.2 Capabilities of an ideal planning system

I made the following assumptions about an ideal planning system.



1. The forecasting is sufficiently accurate for the warehouse to function smoothly and meet all demands if the safety stocks, which are planned saleable stocks, of each brand exceed three weeks sales.
2. Adjustments to the forecasts are made sufficiently early to permit any desirable changes in the labour force, and to prevent excessive stock holdings of any brand.

A forecasting system which estimates the total sales for a machine type over the next nine months to within 10%, and the sales for a brand over the next two months to within 25%, should be suitable for 1 and 2. In practice, these targets may not be achieved (see 13.4.3).

3. The mould scheduling works at maximum efficiency and can maintain unbalanced stocks at their minimum level (see 9.5.3), for a couple of months. This would require a large number of mould changes each weekend. The fitters have never made this number of changes in a weekend, although it is theoretically possible.

4. Production is kept sufficiently close to the product schedule that no stockouts are thereby caused. A reasonable target is to keep the variation for a size below one week's sales.

#### 4.5.3 Improvements in customer service

To make the alternative machine loadings comparable with the actual, I assumed that sales would remain constant despite the better supply. With hindsight it would have been possible to make up to 50,000 more pairs of the canvas shoes in short supply. To evaluate this potential saving, I estimated the stockout cost.

A stockout causes increased administration and handling costs, and a loss of goodwill. I compared the processing of a normal order, and

a delayed order, which may be dispatched in parts, and concluded that direct costs increase by about 20% during a stockout.

The immediate loss of business during a stockout can be estimated from the cancellations. Detailed customer records which might show any long term effects are not available. The sales representatives had a wide spread of opinions on the effect of a stockout, so I took a cautious estimate. Using these figures, the total stockout cost during the year exceeded £5,000. (With less cautious estimates it could be over £20,000). With good forecasts, almost all this loss could have been avoided by increasing production of the affected brands much earlier.

#### 4.5.4 Analysis

Under the assumptions given earlier, I constructed a machine loading schedule which gave near minimum stocks for each brand at the end of the sales season. The loading for the rest of the year was obtained by working forwards or backwards from that time.

This machine loading required the peak level of mould changing for two months, and gave a substantial variation in the labour force. It showed the maximum scope for improvement that was theoretically possible under the assumptions.

Since it is unrealistic to plan for these conditions, I revised the machine loading to give a more realistic situation. I allowed the labour variation to equal the actual labour variation and set the peak rate of mould changing at a level that had been obtained.

Table 3 presents the savings at 1972 prices that could be obtained under this 'ideal' loading, and under the 'maximal' loading given earlier. It also gives realistic savings that could be achieved

with an improved planning system.

The 'maximal' loading saves £2,000 more than the 'ideal'. Two-thirds of this saving comes from the wider variation in labour force, and one-third from the increased mould changing. In practice, the difficulties involved with either of these proposals would increase costs not considered here by more than this, so the 'ideal' loading is preferable.

#### 4.5.5 Realistic savings

A realistic system will not achieve the full savings of an ideal system, but should yield a substantial improvement. It is difficult to change the labour force levels so that it is likely the resource planning will be less efficient than other areas.

Forecasting is unlikely to acquire the desired long term accuracy so that some major stockouts will still occur. A realistic saving here is £2,500 per year.

The excess mould scheduling costs should fall from their current level of 60% to around 25% with a better scheduling system. This improvement will permit stock levels to be reduced by 90,000 pairs without increasing mould scheduling costs, thus saving £5,500. Full details appear in table 3.

A moderate improvement in the machine loading will be needed with the lower stock levels but this should be attainable even under current practice. The 'realistic' plan assumes no further savings here since they are difficult to estimate and implementation may be delayed.

Qualitatively large savings are possible from machine loading if stocks are moderate to high while low savings are likely with low stocks

Table 3 The scope for savings in 1972 under various  
alternative planning systems

<u>Planning system</u>	<u>Maximal</u>	<u>Ideal</u>	<u>Realistic</u>
Variation in labour force (as % of mean)	60	15	15
Peak rate of mould changing (as % of maximum)	100	60	60
Reduction in average stock ('000 prs)	196	158	90
Saving in interest charges at 10% (£)	11,800	9,500	5,400
Saving in production costs (£)	- 100	200	100
Saving in stockout costs (£)	5,000+	5,000+	2,500
Saving in raw material stocks (£)	400	400	0
<hr/>			
Total Saving (£)	17,000+	15,000+	8,000

or demand backlogs. Conversely the potential savings from product scheduling are highest with low stocks.

#### 4.5.6 Conclusions

An ideal planning system would save over £15,000 per year. A realistic system could save over £8,000 per year, mainly in reduced stocks and improved customer service. Recent rises in prices and interest rates make this equivalent to over £10,000 a year now.

This saving is not large enough to justify a team of consultants working on the project. It makes a reasonable target for an I.H.D. Project; the project therefore went ahead.

## CHAPTER 5     PRESENTATION OF THE SUB-PROBLEMS

### 5.1 Introduction

The problem was subdivided in Chapter 2 into sales forecasting, resource planning, machine loading and product scheduling. It was made clear there that only the injection moulding department need be planned.

For the presentation of the problem in this chapter, and its subsequent solution, I have further subdivided it as shown in diagram 11.

Section 5.2 justifies the problem subdivision. The forecasting problem is described in Section 5.3, and the resource planning in Section 5.4.

As an introduction to the scheduling problems, Section 5.5 discusses the value of stocks in production planning. (Section 7.2 gives more detail on this). Section 5.6 presents the machine loading problem, and Section 5.7 the parts of the product scheduling problem. The results quoted here about the form of the planning costs are only justified in the chapters on the relevant problems. Finally, Section 5.8 analyses this subdivision.

### 5.2 The problem subdivision

The production planning system is too large to study as a whole, so it must be subdivided. Nevertheless, the parts should be considered as a whole, for independent optimisation of separate parts is unlikely to yield overall optimality. A good subdivision will yield complete sub-systems whose interactions are understood.



Few books on production planning consider the whole problem. Of these, the structure adopted by Holt et al. (14) is typical. They have two major planning components, aggregate decision making and individual product planning under aggregate constraints. In addition they see forecasting as a necessary input to each component.

With batch production methods, they subdivide individual product planning into setting safety stocks, and finding the optimal batch quantities.

The subdivision I am using (see diagram 11) has the same basic structure as Holt et al. with decisions at a high level based on the likely performance of the lower level(s). An extra stage, machine loading, is introduced because of compatibility constraints imposed by the machinery which make the scheduling problem too large to be tackled effectively in one stage (see 2.4.4). Holt et al. omit capital investment from their model, while I include it in the resource planning due to differing boundaries of the problem.

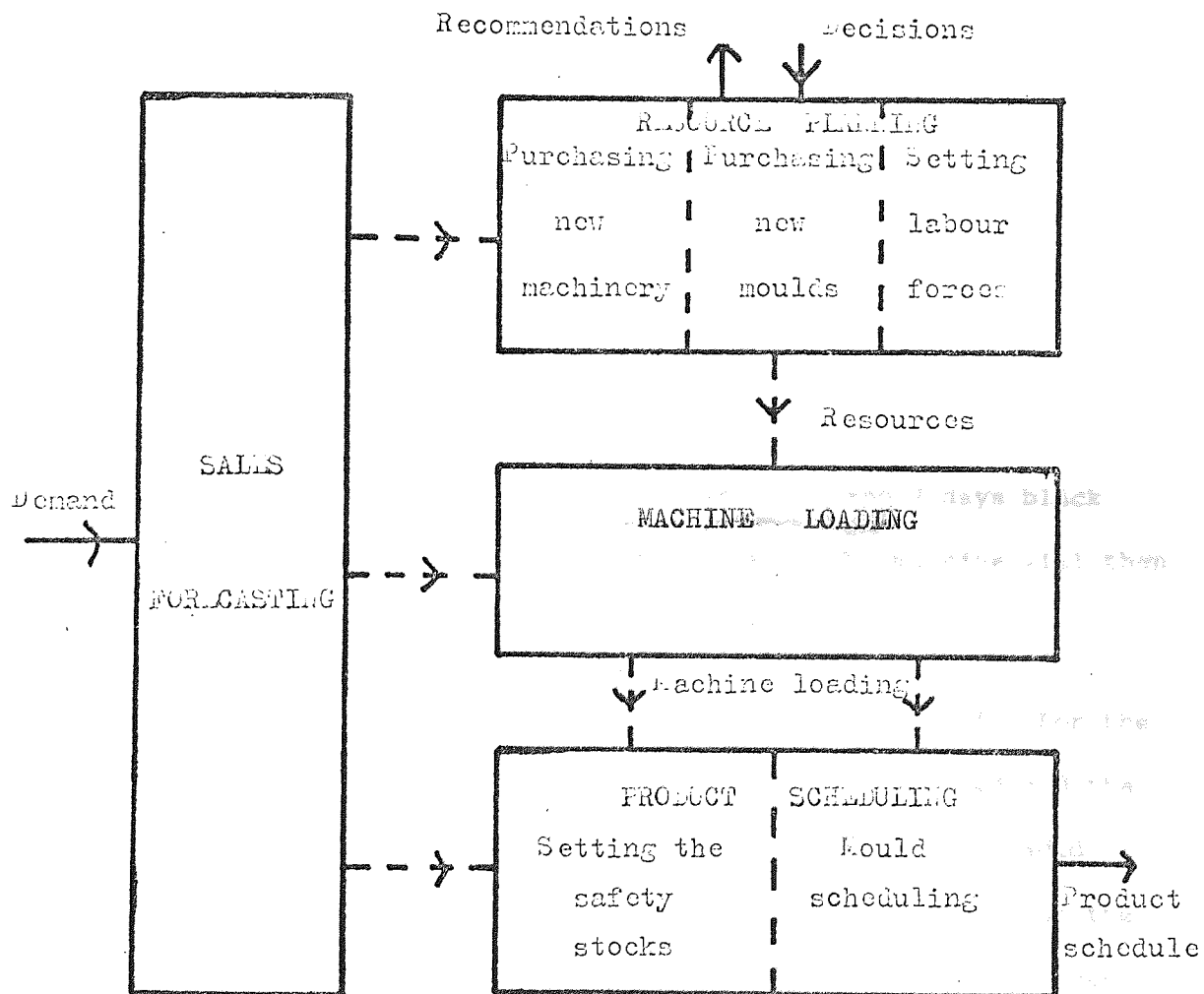
All the parts of the production scheduling have the same objective: to minimise production costs for a given set of resources. Machine loading involves the aggregate production scheduling decisions by machine type and manufacturing group. The individual product scheduling at size and brand level is subdivided into setting the safety stocks and mould scheduling. This is directly comparable to Holt et al. (with mould scheduling equivalent to determining the optimal batch quantities).

The essential difference between this problem and that of Holt et al. is that decisions here are highly constrained while their decisions are completely free. This will affect the appropriate solution techniques.



Diagram 11

FULL SUBDIVISION OF THE  
PRODUCTION PLANNING SYSTEM



### 5.2.1 Production scheduling illustration

There are two manufacturing groups, 'infants' with 5 brands and 'golf' with 3 brands, which are made on the small protective machine. Assume that this is planned to operate 15 shifts per week. Overall stocks are well above minimum but not large. Sizes 5 and 7 red infants will soon be out of stock but otherwise stocks of infants are good. There are plenty of white golf shoes in all sizes but stocks of brown and black golf are generally low.

In the machine loading, 'infants' will be loaded first because their saleable stocks are very low. After two weeks these stocks should be well balanced and saleable stocks will be high so the machine will change to producing golf shoes. The optimal batch quantity of golf shoes is determined from a graph to be four weeks' production which should be split into 3 days white, 10 days brown and 7 days black (lightest colour first) to balance the stocks. The machine will then return to producing 'infants' after six weeks.

Product scheduling is done separately for infants and golf. For the first two weeks of infants, the moulding colour will be red and the size 5 and 7 moulds and probably their duplicates will be loaded together with one other appropriate mould. Nothing happens for the next four weeks, then production will continue with the most urgent brand and sizes.

Product scheduling for golf shoes is done on a daily basis commencing with 3 days of white since, although stocks are currently high, some production is needed to give balanced supplies of golf shoes at the end of the four week run. Brown and black are then produced in turn. The sizes 8 and 9 moulds will be in continual use, occasionally using

a duplicate mould, other sizes will take their turns in the machine.

### 5.2.2 Considerations of implementation

Implementation will occur in stages, so the new modules which are introduced must be designed to operate with existing systems as well as in the new design. Problems are particularly likely within production scheduling since its stages are closely linked.

The output from one stage is the input to the next stage so it is foolish to design any stage until the desired inputs to the following stage are known. The outputs from the whole system are the product schedules so it was decided to commence by designing the product scheduling modules, and then to proceed backwards from there designing each stage to provide the desired inputs for the following stage. This provides the desired emphasis on production scheduling (see 1.9).

Each stage has been designed to operate from a limited set of inputs mostly provided by the current system or from a fuller set of inputs provided by the new system. The precise boundaries between the modules were chosen to minimise the data transfers. This is why for example the optimal split of stock into 'freestock' and 'safety stock' (see 5.5) is determined in the machine loading module rather than the product scheduling.

### 5.2.3 Summary

The proposed subdivision is shown in diagram 11. Its justification is that it is natural, it is appropriate for the environment (see chapter 2) and the objectives (see chapter 3). It yields reasonably self-contained sub-systems which fit together well. Finally considerations of implementation and the emphasis of the project

(see 1.9) suggest that one should commence with the product scheduling, and proceed backwards from there to (aggregate) machine loading and then resource planning and sales forecasting.

### 5.3 Sales forecasting

Sales forecasts contribute to the objectives by providing information for other functions such as production scheduling. The true object in forecasting is to enable these other functions to perform better. Such improvement is often hard to measure, so surrogate forecasting objectives are generally used.

In production planning, it is desirable to avoid stockouts. Appropriate safeguards can be taken if the forecast accuracy is known. These will cost less the more accurate the forecasts. I am assuming, as is conventional, that a forecast will give an expected value for the variable and its likely error. The object is to select a forecasting method which minimises this error.

This is suitable for short and medium term demand. Strategic planning, which requires an understanding of the longer term demand, is not within my terms of reference.

My investigations into forecasting are intended :-

To examine models of the demand system and hence gain an understanding of major influences on it;

To provide good short term forecasts of the demand for each size and brand;

To provide good medium term forecasts of the demand for each brand, for each manufacturing group and, further ahead, for the classes of

canvas shoes and protectives.

#### 5.4 Resource planning

In brief, the problem is to estimate the effects on production planning costs of any proposed changes in the resources. The major costs are labour, capital, storage and shortage costs. Raw materials can generally be obtained at short notice, therefore they are not included within the resources fixed before scheduling. Similarly, production costs, such as mould changing costs, depend more on the scheduling modules.

##### 5.4.1 Background

Resource planning decisions are made outside the planning system by the factory management in response to 'political' and economic pressures. It is unrealistic to expect proposals to be implemented automatically (see 3.5) therefore the resource planning system should be simple and advisory. It is sufficient to provide crude estimates of the change in costs due to a change in resources.

A change in resources will affect the machine loading and product schedule. Its effect can be estimated from the marginal value of each resource in models of these areas.

##### 5.4.2. New machinery

New machinery gives extra capacity. This generates extra profit if demand in a year is likely to exceed current capacity. (The seasonality makes short term increases in demand irrelevant).

Extra machinery also reduces the production costs since more moulds are in use at a time, so fewer changes are likely to be needed.

Gains in these areas must be set against the depreciation on the machinery. Note that the profit will be very sensitive to the forecast used.

#### 5.4.3 Duplicate moulds

There is normally one mould of each size. A duplicate is necessary if the demand for a size is greater than the production possible from a mould while the appropriate manufacturing group is being made.

A duplicate is desirable if the first mould is used almost all the time. It enables a temporary increase in demand to be met. Its value is the potential saving in stockout costs. At present, a third mould is never worthwhile.

#### 5.4.4 Changes in the labour force

There is very little opportunity for overtime as the machinery normally runs full-time (see 1.7.1); therefore the size of the labour force controls the production rate. An increase in the labour force will increase the output and hence the stocks and storage costs. As shown in 5.5, higher stocks will reduce the scheduling and shortage costs. The desirability of an increase depends on the average marginal value of a production hour which is derived during the machine loading (see 11.5.2).

#### 5.5 Introduction to scheduling - the value of stocks

(See chapter 7 for further details)

Stocks separate production from sales. Without stocks one must either produce in line with the demand or sell as one produces.

Stocks perform three major functions. They smooth the production levels by increasing as demand falls and vice-versa; they reduce stockouts due to unexpectedly high demands; and they permit batch production. Resource planning uses the first property of stocks; the seasonality of demand is absorbed by varying the stock levels with a constant labour force. The other properties conflict.

The minimum planned stock of a product is called its 'safety stock', the stock in excess of this is its 'freestock'. To reduce stockouts, the 'safety stocks' of each product should be high. To reduce production costs, the average 'freestock' should be high. For example, by producing in batches the planned stock of a product varies between the 'safety stock' and a higher level, the excess being 'freestock'. As the batch quantity and hence the average 'freestock' increases, the frequency of mould changing decreases thus reducing production costs.

The expected stock at any time is fixed by the available resources, therefore a major part of the scheduling solution is to determine the optimal division of the stock into 'safety stocks' and 'freestocks' and, within this partition, to divide the stock optimally between the products.

#### 5.6 Machine loading

With the resources as specified by the 'resource planning', and assuming the 'product scheduling' performs as expected, the 'machine loading' problem is to determine a feasible machine loading for the injection moulding department which minimises the expected total of the production, storage and shortage costs over the scheduling period.

In addition, for each manufacturing group one must specify the optimal split of the aggregate stock into 'freestock' and 'safety stock'. Note



that these will vary weekly as the aggregate stock alters. This contrasts strongly with the normal concept of fixed safety stocks.

#### 5.6.1 The resources

The resource planning specifies the available machinery and moulds. It also determines the labour force and the number of hours each gang will work each week. It may specify which machines are to be run.

#### 5.6.2 The machine loading

The products are grouped into manufacturing groups of compatible items; all products made from a machine at one time must be compatible (see 2.4).

A machine loading schedule states the manufacturing group to be made in each machine during each period (generally a week long - see 8.5). It also states if the machine is to be run continuously or only for part of the period. It may specify the moulding colours; if not these are freely set by the mould scheduling module.

The exact production, storage, shortage and expediting costs depend on the mould schedule but, assuming this performs as prescribed, the costs can be aggregated at manufacturing group level. Details are given in section 11.2.

#### 5.6.3 Feasibility

A feasible machine loading meets all the constraints imposed on it. There are two common forms of constraint, constraints on specific actions and constraints on cumulative supplies.

A typical specific constraint is that some manufacturing groups may not be made together where this would overload the 'finishing' department. Also, the number of machine changes at a weekend is limited by the availability of fitters.

If the supply of some raw material is limited, the cumulative production of products using that material is limited. For example, golf studs arrive at a uniform rate, so a three-week run on golf shoes would need to be scheduled later than a two-week run.

## 5.7 Product scheduling

Given the machine loading, the product scheduling problem is to schedule the production for the injection moulding department to minimise the production, storage and shortage costs over immediate and future periods.

### 5.7.1 The product schedule

A product schedule states the five products to be made on each machine in each period. Each product is a certain size of a certain brand; it therefore requires a specific mould and specific injection colours.

A product schedule yields a mould schedule stating the moulds required in each machine and the colours for injection. The production costs depend mainly on this mould schedule.

### 5.7.2 The costs associated with a schedule

The same costs, production, shortage, storage and expediting, arise in product scheduling and in machine loading. The latter were aggregate costs; these are now related to individual sizes and brands. Storage and expediting costs are straightforward.

#### 5.7.2.1 Production costs

The injection moulding production costs which vary with the schedule are chiefly the mould and colour-changing costs. The mould-changing cost depends on the manufacturing group and time of week but not the mould. Colour-changing costs depend on whether the new colour is lighter or darker.

There are also minor costs for changing from one brand to another while using the same mould. Such costs can be ignored providing such changes are not excessive (not more than once per mould per week).

The machine efficiency depends on the mix of moulds in use. As explained in section 8.3 it is costly to run a wide range of moulds, such as child's and men's, together.

#### 5.7.2.2 Shortage costs

Shortage costs are incurred if any size is out of stock. Unless stocks of one size are exceptionally low for a special reason, each size is potentially a 'critical' size.

Within a brand, the shortage cost associated with the planned stock of each size is estimated as the probability that that size is critical multiplied by the cost of a stockout in that brand. The shortage costs thus depend on the safety stock policy by size and brand.

#### 5.7.3 Breakdown into sub-problems

The major variable costs at product scheduling level are production and shortage costs. These are respectively related to the 'freestock' and 'safety stock'. The optimum division of the aggregate stock is

determined within the machine loading module. This division permits the production and shortage costs to be considered separately and gives the product scheduling two sub-problems.

#### 5.7.3.1 The safety stock problem

Knowing the mould scheduling policy (see below), and given the aggregate safety stock, the object is to set the safety stocks for each size and brand to minimise the expected shortage cost.

Note that the aggregate safety stock, and hence individual safety stocks, may vary from week to week.

#### 5.7.3.2 The mould scheduling problem

Define the 'scheduling requirements' for each size and brand as the expected cumulative demand plus the safety stock. Ideally one starts production of each product as its 'freestock', which is its stock in excess of the scheduling requirements, falls to zero.

The scheduling requirements can be violated since the division into 'freestock' and 'safety stock' is not absolute, but there is an associated penalty cost. The object in mould scheduling is to minimise the production plus penalty costs while working within the machine loading.

The main constraints on the mould schedule are that each machine must contain five moulds each week, and that the products made together from a machine must all be of the same manufacturing group and colour, as determined by the machine loading.

### 5.8 Analysis of the problem subdivision

Like many large problems, this problem must be simplified and subdivided

before it can be tackled. Many minor points have been omitted from the resulting models. The decomposition of the problem should not harm the solution. The models are linked by aggregate measures. There will be inconsistencies between the actual and aggregate values but these should be minor, and performance measures are used to confirm this.

Feedbacks ignored in the models are the effects of shortages on demand, and the differences between estimated and actual mould scheduling performance. The satisfactory performances of the sub-systems, presented in chapter 15, indicate that the models are acceptable.

## 6.1    Introduction

Chapter 5 completed the definition and background of the problem. This chapter commences the second part of the thesis which concerns the analyses and proposed solutions of the problems.

This chapter explains why the solution approach I use for the machine loading and mould scheduling modules differs from the standard approach one would expect. My approach concentrates on obtaining a feasible solution in all circumstances, and sacrifices some optimality in so doing.

Section 6.2 explains the virtues of an optimal solution. Section 6.3 examines the standard approach and a deficiency of it - that the solution to the model may in practice be infeasible. Section 6.4 explains why, for the production scheduling modules, this deficiency could be serious. This led me to adopt my approach (see 6.5) which almost always produces feasible solutions.

## 6.2    Why optimise?

In decision making, companies generally accept a solution to a specific problem if it reaches their minimum requirements on all criteria (see 3.2). This behaviour is called 'satisficing'.

Nevertheless it is reasonable to assume there is an optimum or set of optimal equally preferred solutions. In realistic circumstances, if the company is either indifferent between alternatives or can express a preference for one, and if such preferences are rational (i.e. A is

preferred to B, and B to C implies A is preferred to C), there will be at least one optimal solution.

When a researcher has a problem to solve, his ideal is to find an optimal solution. His problem is that the decision makers cannot express their preferences abstractly, nor even afford the time.

Furthermore, if preferences are not rational, no optimal solution need exist.

### 6.3 The 'standard' approach

The 'standard' approach, when seeking an optimal or near optimal solution, is to construct a model of the problem. This model, which need not be explicitly created, incorporates the researcher's interpretation of the company's preferences. The model is then solved and the optimal solution to the model is presented to the company as the solution to its problem.

Since no model is completely accurate, this solution will not in practice be optimal. It may be rejected as unsatisfactory or infeasible because it ignores certain hidden preferences of the decision makers.

In practice, with a reasonable model, its solution can generally be adjusted by the decision makers to give a feasible and near-optimal solution to the true problem. To do this, it is helpful if the sensitivity of the solution to small changes in the variables is known.

### 6.4 Infeasibility of the standard approach for the production scheduling modules

My enigma with the production planning system at Dunlop Footwear arises from the large number of potential constraints on feasible schedules.



This applies particularly to the machine loading module, but also to the mould scheduling module.

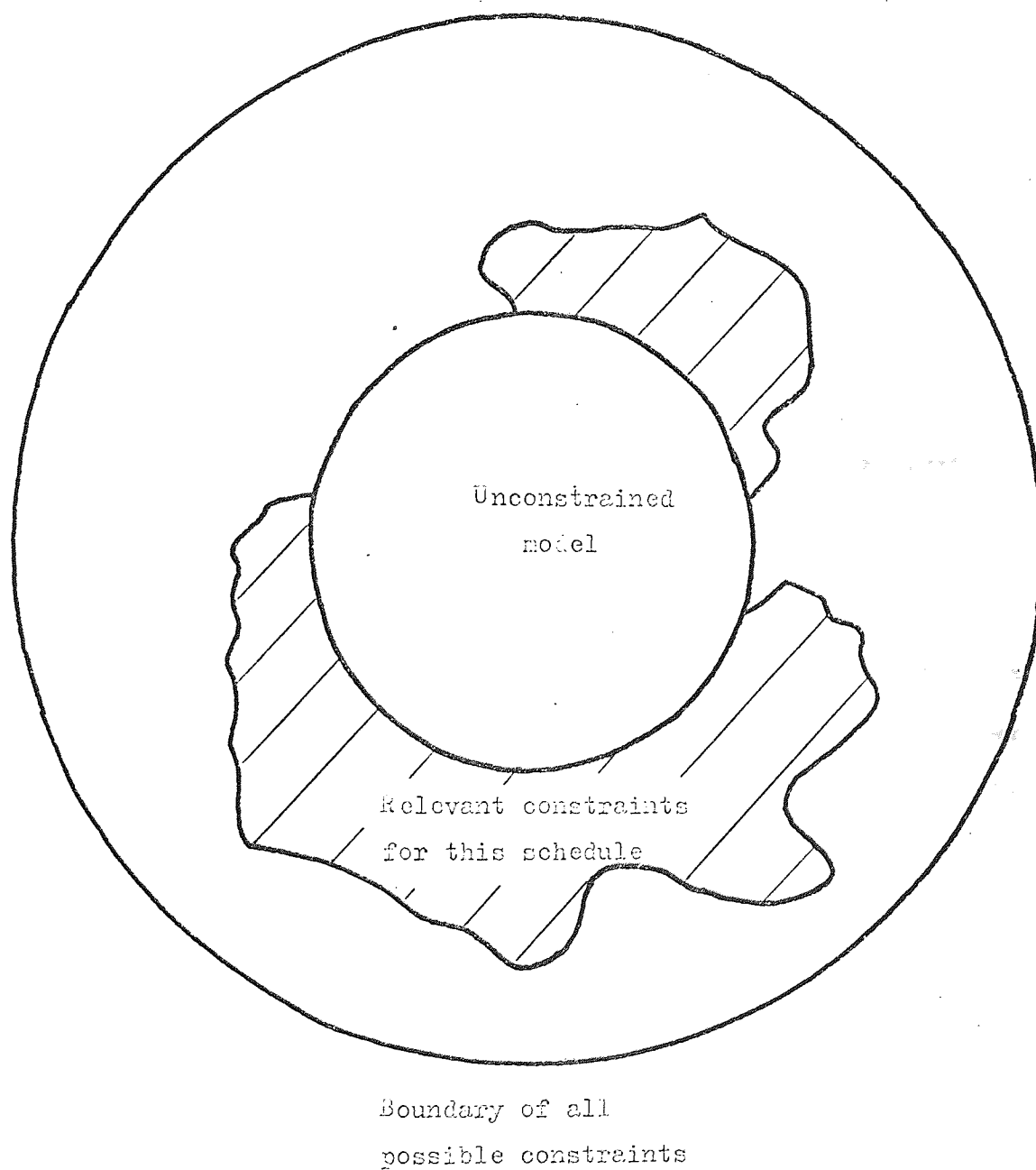
Each problem can be represented as an unconstrained standard problem in an ocean of potential constraints with a small and varying set of relevant constraints for each schedule (see diagram 12). Appropriate models correspond to each representation of the problem.

A standard approach, based on the Economic Batch Quantities (see 9.3), can model and solve the unconstrained standard problems. These models rank alternatives almost identically to the management, so that their best solutions which are also feasible should be nearly optimal in practice.

However solutions to the unconstrained model are rarely feasible, and manual adjustments to yield a feasible solution are usually far from optimal since the best feasible solution is often very different from the unconstrained solution.

This implies that the models should be extended to include relevant constraints. It would be desirable to model and solve the general problem which contains all types of potential constraint. The constraints cannot be classified under a narrow range of headings, indeed while I was considering this approach several new types of machine loading constraint were revealed, so it is not practical to produce this macro-model. Therefore the appropriate model must be identified each time.

The solution technique should be capable of handling all potential models. The standard approach gives exact solutions for a restricted set of models with no feasible solutions in other cases. My object has been to produce good (nearly optimal) solutions for (almost) all constrained



models of the problem. In other words, I am seeking a robust approach.

#### 6.5 My approach

There are no known exact solutions to general forms of the scheduling problem except for methods based on a full or systematic partial search. Section 9.4 describes such a solution to the unconstrained mould scheduling problem. Unfortunately this method is very slow and cannot readily cope with the general constrained problem.

My solutions to the scheduling problems use priority systems scheduling one period at a time. Each item is given a priority based upon its desirability for production. Items are scheduled in order of priority.

The priority is based on certain assumptions about the future. These are only exact for simple forms of the unconstrained model, therefore the solutions while good (see 15.7) are unlikely to be the best.

Priority methods are very flexible: almost all constraints can be incorporated by the use of large negative priorities, and manual adjustment to the next best solution uses the item of highest priority not yet scheduled (rescheduling may be advisable for subsequent periods). Priority methods are therefore robust and have been adopted for the reasons stated in 6.4.

CHAPTER 7    INTRODUCTION TO THE PRODUCTION  
SCHEDULING SOLUTIONS

7.1    Introduction

This chapter summarises the production scheduling solutions to be presented later so that in studying the detail one understands the general context.

The solutions are derived from standard solutions to certain simple scheduling problems. These standard solutions are introduced in section 7.2 by means of a standard production scheduling problem. This explains why safety stocks and batch quantities to manufacture are generally considered separately. It gives algorithms to calculate the optimal safety stocks and batch quantities. These specific algorithms are not used in my solution but underlie my approach.

Section 7.3 is rather different from the rest of the chapter. It summarises the results of chapter 8 which deals with the effects of the production process on production planning. Apart from these effects, the process can be ignored.

The scheduling problems were presented in progressively more and more detail. However the solutions are first produced for the lowest and most detailed level, mould scheduling (see 5.2.2); aggregate properties of this solution are later used in the machine loading. Correspondingly the associated chapters now appear in the reverse of their earlier order.

Section 7.4 outlines the mould scheduling solution presented in chapter 9. The solution employs the Economic Batch Quantities as derived in 7.2.2, but a priority system is actually used to produce the mould schedules.

Section 7.5 introduces chapter 10 which concerns the optimal policy for setting safety stocks. Similarly section 7.6 outlines the machine loading solution as given in chapter 11. ~~and performance will decrease~~

This section also divides the manufacturing groups into two classes according to the frequency of production since the machine loading solution varies for high and low production manufacturing groups.

Note that both the mould schedule and machine loading solutions are constructed one period at a time. This gives the maximum flexibility and permits constraints to be inserted easily (see chapter 6).

The final section, 7.7, gives an idea of the improvements arising on partial implementation of the proposed solutions. Full details are given in chapter 15.

## 7.2 A standard production scheduling problem

Consider the production scheduling problem of a manufacturer who produces in batches and sells to customers from stock. He wishes to minimise his present and future costs.

Assume the only significant scheduling costs are storage costs, which depend on the average stock held; set-up costs at the start of each batch; and shortage costs incurred if the demand exceeds stock. The revenue and production cost per unit are assumed constant and can be ignored. There are no significant constraints on scheduling. Linear storage and shortage costs are assumed although the general results apply also if the marginal costs are non-decreasing. (The costs are then convex.)

Two balances are involved in scheduling. As the minimum stock is

increased (for a given batch size) the shortage costs will decrease and the storage costs increase. As larger batches are run the storage costs will increase but the set-up costs per period will decrease.

The two balances are not independent since large batch sizes imply that the minimum stock is reached less frequently and hence can be lower while giving the same protection. Nevertheless it is convenient to consider each balance separately.

Assuming that the demand for each product varies randomly around a fixed level it can be shown that the minimum future cost is a convex (U-shaped) function of the net stock (the total stock less unsatisfied demand). The optimum scheduling policy has the form 'schedule a new batch to bring the stocks up to  $S$  when the expected stock falls below the safety stock,  $s$ '. This is called an  $(s, S)$  scheduling policy (15).

#### 7.2.1 Safety stocks

Safety stocks protect one against shortages due to high demand. They are appropriate if customers will be dissatisfied if their orders are not met from stock.

To calculate the appropriate safety stocks the distribution of sales per period should be known. As safety stocks increase their marginal value falls; the optimal safety stocks give a marginal improvement in customer service equal in value to the storage cost.

For example, if the shortage cost per unit is constant then at the optimum safety stock the probability of a stockout equals the ratio of the storage to storage plus shortage costs. This problem is commonly known as the newsboy problem in the literature (e.g. 16).

The newsboy has to decide how many spare papers to purchase each day to maximise his profit.

### 7.2.2 The Economic Batch Quantity for production

The safety stocks cover the variability in demand, so that one need consider only the planned stocks in excess of the safety stock, which I call the 'freestock', and one can assume a fixed sales rate in setting the batch size. This ignores a slight interaction between batch sizes and safety stocks.

The average storage cost is proportional to the batch quantity, since a batch will start when the 'freestock' is zero. The average set-up cost depends on the frequency of set-ups and hence inversely on the batch quantity. Diagram 13 shows how the costs vary with the batch quantity: at the minimum, the marginal decrease in set-up costs equals the marginal increase in storage costs.

The calculations below evaluate the ideal batch quantity using the accompanying notation (17). A property of these assumptions is that, for the ideal batch quantity, the average storage cost equals the average set-up cost.

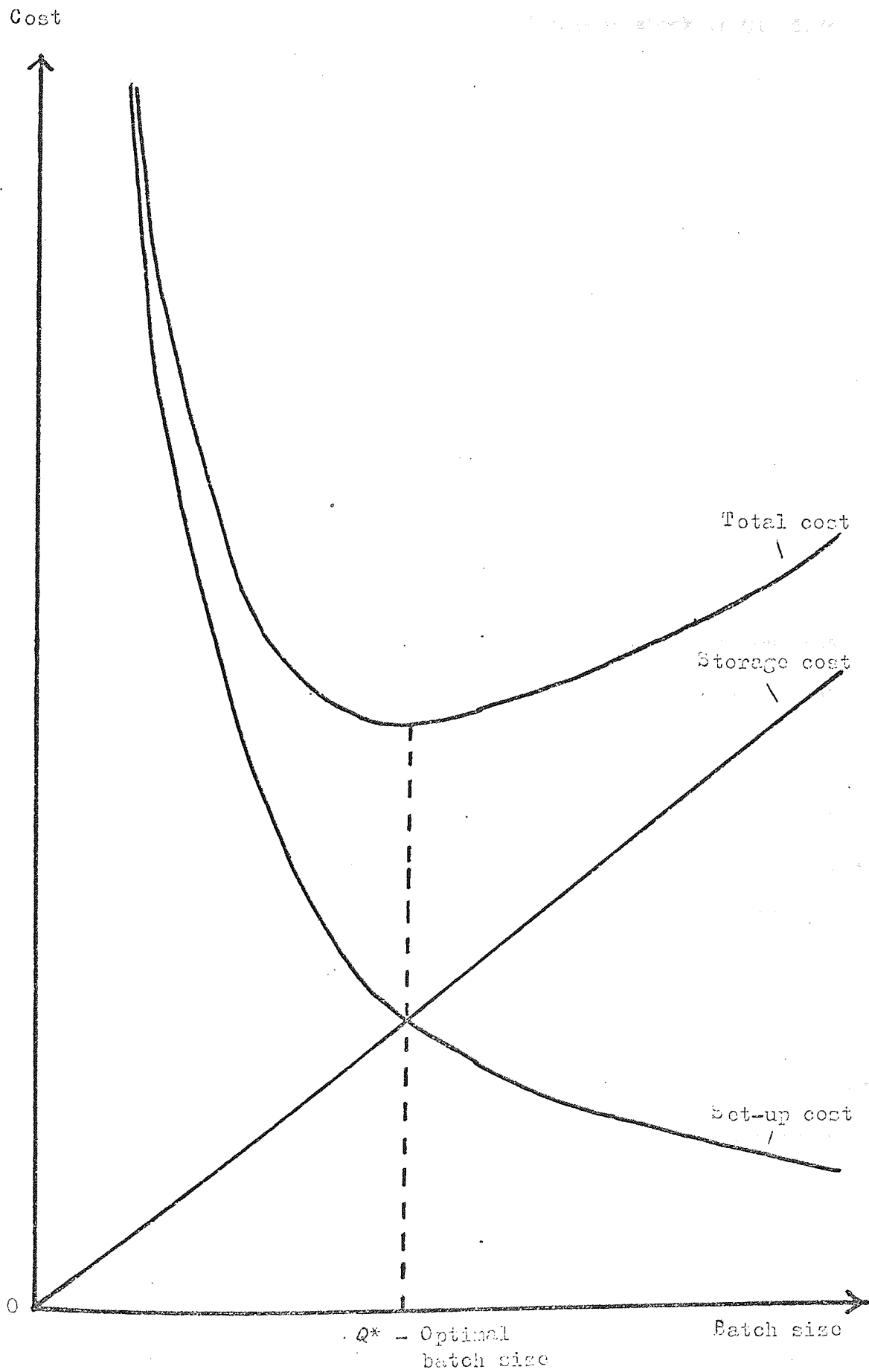
Sales rate	$d$
Production rate	$p$
Average 'freestock'	$A$
Batch quantity	$Q$
Storage-cost per period	$c$
Set-up cost	$K$

The average interval between set-ups is  $Q/d$ , so the set-up cost per period is  $Kd/Q$ . The average storage cost per period is  $cA$ . One wishes to minimise  $cA + Kd/Q$ .



Diagram 13

PRODUCTION COSTS AS A FUNCTION OF BATCH SIZE



A new batch is started when the 'freestock', the planned stock in excess of the safety stock, equals zero. Production takes a time  $Q/p$  during which the demand is  $Qd/p$  so the peak stock is  $Q(1-d)/p$  and the average stock,  $A$ , equals  $\frac{1}{2}Q(1-d)/p$  (see diagram 14). Note for future reference that the average freestock,  $A$ , required by a given mould is directly proportional to its batch quantity,  $Q$ .

The marginal storage cost is thus  $\frac{1}{2}c(p-d)$  and the marginal decrease in set-up costs is  $Kd/Q^2$ . Equating these gives an optimal batch quantity  $Q$  equal to  $\sqrt{2Kdp/c(p-d)}$ . This is the Economic Batch Quantity or E.B.Q.

### 7.3 Effects of the production process

(Introduction to chapter 8)

The production process has three significant effects on production scheduling, otherwise it can be ignored. The first effect concerns the timing of mould changes, the latter two relate to the fact that each machine holds several sets of moulds.

Firstly, changing a mould is a slow process especially on the large machines, therefore this is normally done out of production time, i.e. at the weekend (see 1.7.1). Thus batch sizes are almost always a multiple of the weekly production, and schedules can be issued in weekly units.

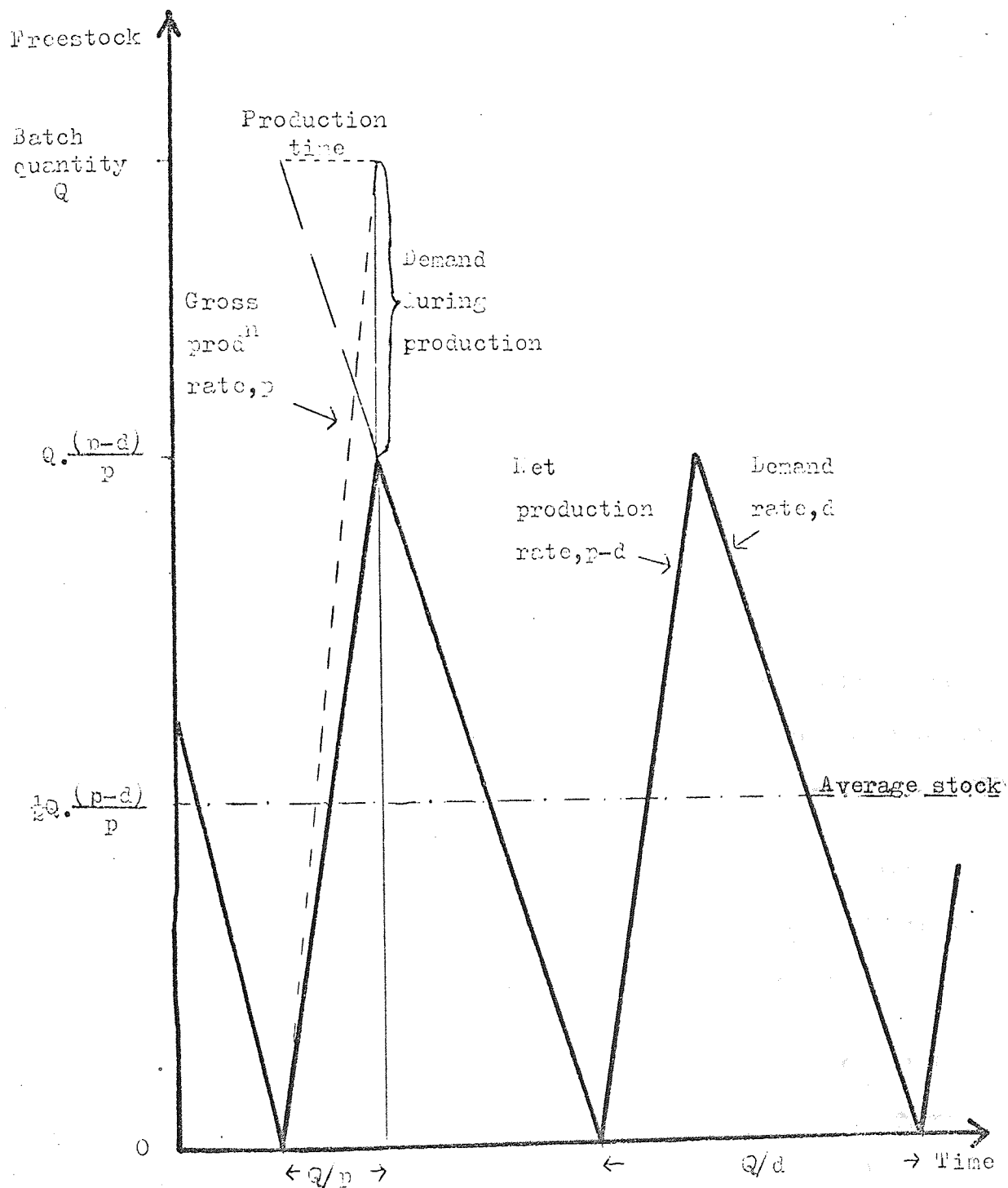
The second effect was introduced in section 2.4, and led to the concept of a 'manufacturing group'. This is that all moulds in a machine must be compatible, and that products made at one time from one machine will all have the same colours.

The final effect arises because the ideal settings of the machine vary

Diagram 14

FLUCTUATIONS IN THE STOCK LEVEL

UNDER BATCH PRODUCTION



with the mould capacity. The injections will not be completed if the settings are not appropriate for the largest mould in the machine; this mould therefore determines the machine settings including the output rate or 'cycle time'. The quality of the output from any mould depends on the difference between the actual and ideal machine settings. Low quality output is downgraded or even rejected.

The loss of output from a poor mix of moulds does not significantly reduce the production rate, so in scheduling a fixed production rate can be assumed. However the cost of the lost output and increased number of rejects is significant. I have called this the 'size-mix' cost.

The 'size-mix' cost depends on the differences in volume between the actual and ideal moulds in the machine. The estimated cost (see 8.8) is low for small differences in volume, but rises rapidly once a critical difference is reached.

#### 7.4 Mould scheduling

(Introduction to chapter 9)

Mould scheduling is essentially the determination of the moulds to be in each machine at any time and the products to be made from each mould. This may include deciding the production colours for each machine.

Mould scheduling is here performed in two stages. The ideal batch quantity for each mould, given a value for the total 'freestock' from the machine loading module, is calculated in the first stage.

In the second stage the mould schedule is prepared for one week at a time. The moulds to use and products to make are selected on the basis of the previous mould loading, the expected stocks, the ideal batch quantities and any shortages of raw materials.

The mould schedules are prepared independently for each manufacturing group since no two groups will share a machine and since any competition for resources, such as labour or a specific raw material, is resolved in the machine loading (Chapter 11).

#### 7.4.1 Allocating the available freestock

As noted in section 7.2.2, the average freestock for any given mould is directly proportional to its batch quantity. Therefore the total freestock would be determined if the batch quantities were set equal to the Economic Batch Quantities. However, the total freestock is determined by the machine loading.

Examination of the E.B.Q. formula reveals that, as the storage cost is increased, all the optimal batch quantities are reduced as is the total implied freestock. The new batch quantities are optimal for this particular value of the freestock.

The optimal batch quantities are found by appropriate adjustment of the storage cost. Used in this manner the storage cost is called a Lagrangian multiplier. The difference from its true value represents the implicit value of further stock (and hence of further production) (see 18).

#### 7.4.2 Preparing the weekly mould schedule

The ideal production schedule would start each product as its stocks fell to its safety level (i.e. as its freestock became zero) and would continue with each mould until the ideal batch quantity had been produced.

Unfortunately this ideal is impossible because one mould will rarely

complete its ideal production just as another mould is needed.

A common solution is to establish a fixed production cycle for the moulds, but this requires steady production and demand which do not occur here.

The solution adopted calculates a priority for each mould based on its current status, (in production or not), the expected freestock of its most urgent product, and its ideal batch quantity. The moulds and associated products are scheduled in order of priority.

One is aiming to minimise the net present and future costs. The priority is related to the expected gain from production of the mould now rather than on the next most suitable occasion. Future costs are estimated by assuming that the ideal batch quantities are produced in subsequent production runs.

Additional costs, such as the 'size-mix' cost and expediting costs, alter the priority, and most constraints can be included as a large negative priority so the method is very flexible.

Although the machine loading module specifies the division of stock into 'freestock' and safety stock, this division is not absolute.

Slight variations in these stocks should hardly alter costs since their marginal values are equal. The priority system therefore permits one to dip into the safety stocks but this will only occur rarely.

#### 7.4.3 Details of implementation

The actual algorithm I use is more complex than this explanation. For example, a mould is not scheduled if it cannot go into a suitable machine.

The algorithm assumes an infinite scheduling horizon and schedules on

that basis, a revised priority is used near the end of the schedule. Tests on the algorithm show that, except for very short schedules, it produces better schedules than were obtained manually.

Where a manufacturing group remains continually in production, the algorithm schedules at near the theoretical minimum cost. Since this forms the major scheduling problem, the algorithm was adopted and has been coded into a computer programme (see appendix 8).

One cannot expect a reschedule after every alteration to the schedule, because of a breakdown for example, so methods of intelligent manual adjustment are part of the mould scheduling system, see the handbook supplied as appendix 3.

## 7.5 Setting the safety stocks

(Introduction to chapter 10)

The ideal safety stocks provide the best balance between shortage and storage costs (see 7.2.1). In this problem an additional restriction is imposed by the machine loading module which specifies the aggregate safety stocks for all products in a manufacturing group. This aggregate may vary with time.

An unusual feature of the solution is that the safety stocks vary frequently whereas most textbooks consider them as fixed, to be put aside and drawn upon only when necessary. Here, in effect, the demand is met from the 'safety stocks' which are in turn replenished from the 'freestocks'. When the 'freestock' of a product falls to zero, production recommences to rebuild it.

### 7.5.1 The approach followed

A theoretical study of the shortage costs under certain reasonable



assumptions (see 10.3 and 10.4) shows that the ideal safety stocks should vary as an elaborate function of the sales and production rates and many other factors.

A study of these costs suggests that it might be appropriate to allocate the safety stocks between sizes in proportion to the demand. Administratively this is a very convenient solution, so it was implemented. Section 10.6 describes the success of this policy.

It is unsatisfactory to allocate safety stocks between all the brands in proportion to demand for example because some brands are sold only to priority customers. Thus with low aggregate safety stocks one concentrates on priority brands, and with high stocks on brands which are cheap to stock and have an assured market.

#### 7.6 Machine loading

(Introduction to chapter 11)

The machine loading problem is to specify the manufacturing group to be made in each machine during each week to minimise the expected aggregate production, shortage and storage costs for a given set of resources, including a specified labour force. Note well that this implies that the aggregate stocks of all manufacturing groups cannot be significantly altered by the production planner. He controls only the distribution of these stocks between manufacturing groups.

The solution is prepared manually in several stages following the guidelines supplied as appendix 4. The first stage is to build a realistic model relating the expected costs to the aggregate stock. This need only be done once for each manufacturing group and can be revised if circumstances alter.

The major costs are production, storage and shortage costs but their relative importance depends on the aggregate stock; e.g. shortage costs are high with a low net stock. The best solution technique to use depends on these relative costs. The second stage is therefore to identify the appropriate solution technique to use at any time.

The machine loading is prepared in monthly instalments for up to six months ahead. The provisional machine loading for each month is prepared using the appropriate solution technique identified as above; the planning manager then checks and amends it to remove any unacceptable features, e.g. too many machine changes in a weekend. He then proceeds to the next month.

The machine loading is normally revised every four to six weeks. The materials for the next two to four weeks will already be prepared, so the machine loading is rarely altered for this period. The important decisions are the machine loadings for the second and third month, since these are 'firm' decisions.

#### 7.6.1 Aggregate costs

The aggregate costs are assumed to be a function of the net stock, which is the total stock less unmet demand. The shortage cost in fact depends solely on the unmet demand, and the storage cost on the total stock. With good planning, unmet demand should decrease as stocks increase; therefore, since all figures are estimates of future values, this assumption is realistic.

##### 7.6.1.1 Storage costs

Actual storage charges depend on the size and brand, but are similar within a manufacturing group, furthermore the mix of stock within a group remains fairly constant in time. Storage costs for each

manufacturing group, which include interest charges, are therefore assumed proportional to the net stock.

#### 7.6.1.2 Shortage costs

The shortage costs for each brand are assumed proportional to the unsatisfied demand, which in turn is assumed to depend on the net expected saleable stock (see 2.2).

This saleable stock is the safety stock (although it may in fact be negative if demand is high). The safety stock module (see chapter 10) ensures an appropriate distribution of the aggregate safety stock for a manufacturing group, so shortage costs are assumed to depend only on this aggregate net saleable stock.

#### 7.6.1.3 Expediting costs

Sufficient raw materials are normally available, if not they will be expedited. Expediting is likely if production is brought forward or significantly increased. Its cost is the product of the extra quantity required and the excess cost of purchasing or making it.

#### 7.6.1.4 Production costs

The aggregate production costs depend on the nature of the manufacturing group. Class one manufacturing groups are those almost continually in production. For these groups each mould may be used several times in a run and the batch quantity will depend on the available freestock. A larger freestock would enable the batch quantities to be increased, and thus production costs vary inversely with the freestock. In addition, a set-up cost is incurred on

set-up; this covers the cost of the initial machine change.

Class two manufacturing groups are made in short batches. Each size of each brand must normally be produced during each run, this defines a minimum cost for each production run. Since the total requirements of each product are small, the full quantity of each size and brand can be made in one batch, thus it is rarely necessary to exceed this minimum cost, which includes the set-up cost.

The distinction between class one and class two manufacturing groups is very important. Table 4 summarises the results of this section and section 11.2.

Table 4      Differences between class one and class two  
manufacturing groups

	Class 1	Class 2
Demand	High	Low
Production	Almost continuous	In small batches
Production costs	Set-up cost on machine change. Weekly costs depend on the 'freestock' for the manufacturing group	Each product is normally made once in each batch. The total production costs are virtually constant and are independent of the batch size and freestock

#### 7.6.2      Outline of the general solution approach

A proposed machine loading specifies a division of the aggregate net stocks into 'safety stock' and 'freestock' for each manufacturing group. An optimal machine loading is one such that no adjustment will decrease

the expected present and future costs. *estimated opportunity costs.*

*real machine loading is*  
The immediate costs are convex functions of the 'safety stock' and 'freestock'. Without the set-up costs, total costs would also be a convex function of these stocks. The optimal solution is likely to resemble the solution ignoring set-up costs, except that each manufacturing group must be manufactured for an appropriate period determined from the aggregate cost curves.

#### 7.6.2.1 The optimal division of the aggregate stock

At the optimal division of the aggregate stock to minimise immediate costs, the marginal value of stock for each manufacturing group is equal. Furthermore the marginal values of 'safety stock' and 'freestock' for each group are equal. This rule specifies the 'freestock' for the mould scheduling module and the 'safety stock' for the safety stock module once the machine loading is known.

#### 7.6.2.2 Opportunity costs

If the state minimising costs next month can be reached from the state minimising immediate costs, then it is possible to minimise immediate and future costs simultaneously.

Occasionally it may not be possible to reach the state which minimises future costs from the state which minimises immediate costs. The extra future costs are 'opportunity costs' associated with the decision to minimise immediate costs. Such costs are most likely to occur just before the sales peak when the wrong production decision may cause shortages of another product.

The optimal state at the end of each month is defined as the state

which minimises immediate costs plus estimated opportunity costs, which are normally zero. The provisional machine loading is constructed around these optimal states.

#### 7.6.2.3 The provisional machine loading

The difference for each manufacturing group between the expected stocks at the start of a month and the optimal final stocks plus expected sales is the desired production. Each class two manufacturing group is produced if the desired production exceeds a trigger value for that group; the quantity to produce is read off a graph constructed from the aggregate costs.

All class one groups are likely to be manufactured. The appropriate quantity to produce will bring the final stocks near to their optimal value and make full use of the machines after allowing for the class two groups.

#### 7.6.2.4 Adjusting the machine loading

Since the marginal values of each manufacturing group are similar around the optimal state, the machine loading can be adjusted without significantly increasing the costs.

This freedom allows one to provide a reasonably balanced workload for all the workforce instead of the peaks that might otherwise result. In addition any specific constraints can be observed. The planning manager makes any necessary adjustments to give the planned machine loading for the month. He then starts again with the following month.

## 7.7 Effectiveness of the scheduling solutions

This section provides some idea of the improvements resulting from the new scheduling system. Full details appear in chapter 15.

A major concern of production scheduling is to ensure that an adequate supply of saleable stock is maintained to meet the demand. A measure of success is shown by examining the quantities back ordered or cancelled against the total stock. One would expect the unsatisfied demand to rise as stocks fall, but as diagram 15 shows, both back orders and total stocks fell sharply on the introduction of the new scheduling system. This has greatly reduced total costs although scheduling costs have risen slightly (see below).

Part of this success is due to better control and more appropriate safety stocks and part to improved mould scheduling. Diagram 16 shows the boundary of attainable mould changing levels for different freestocks. The new mould scheduling system operates near this curve instead of well above it.

Scheduling costs have increased because we have moved to a more appropriate part of the curve where mould changing costs are higher, but storage costs are much lower.



Diagram 15

CHANGES IN THE RELATIONSHIP BETWEEN TOTAL STOCK  
AND QUANTITY BACK-ORDERED FOR MAJOR MANUFACTURING  
GROUPS ON INTRODUCTION OF THE NEW SCHEDULING SYSTEM

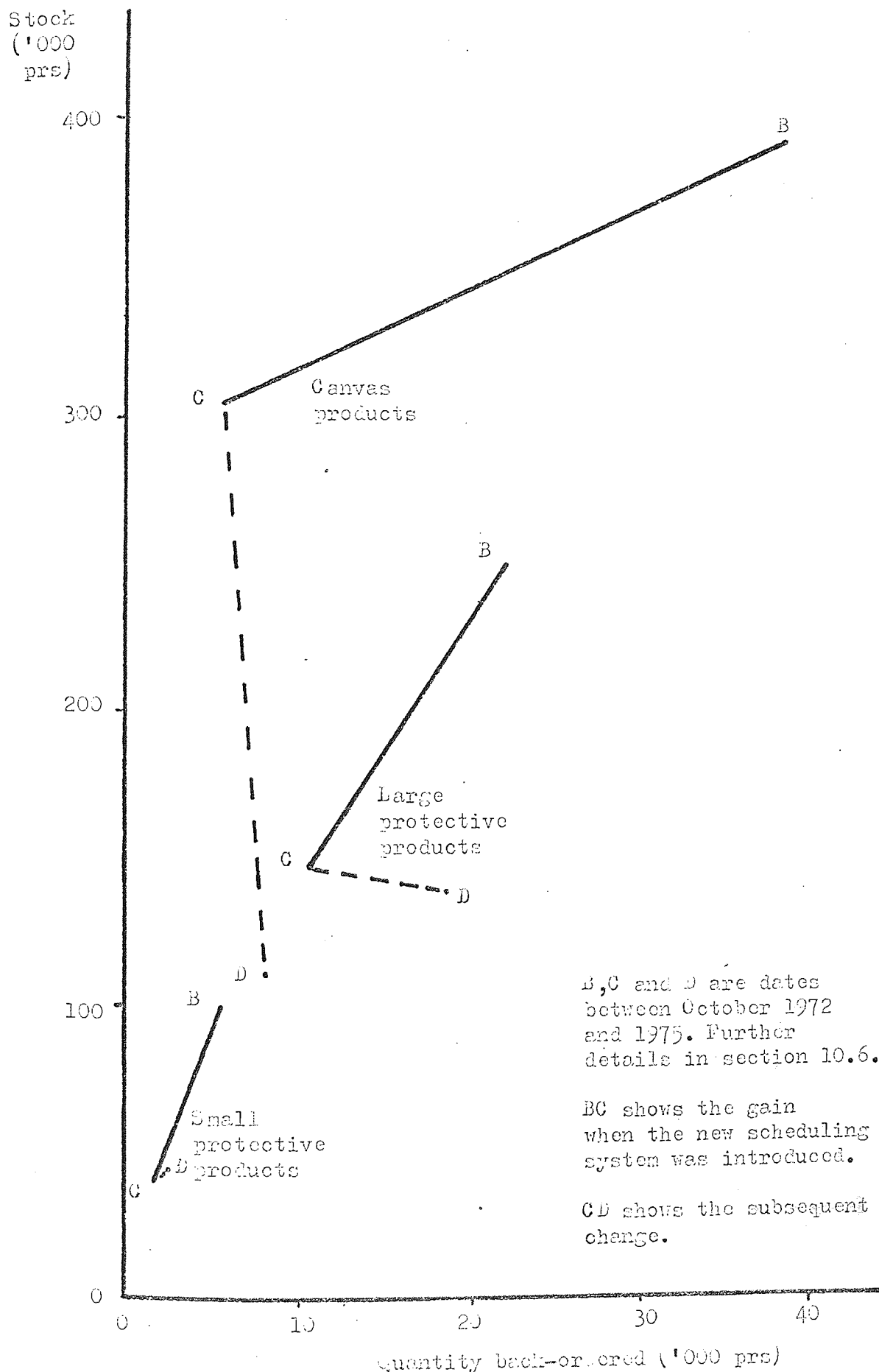
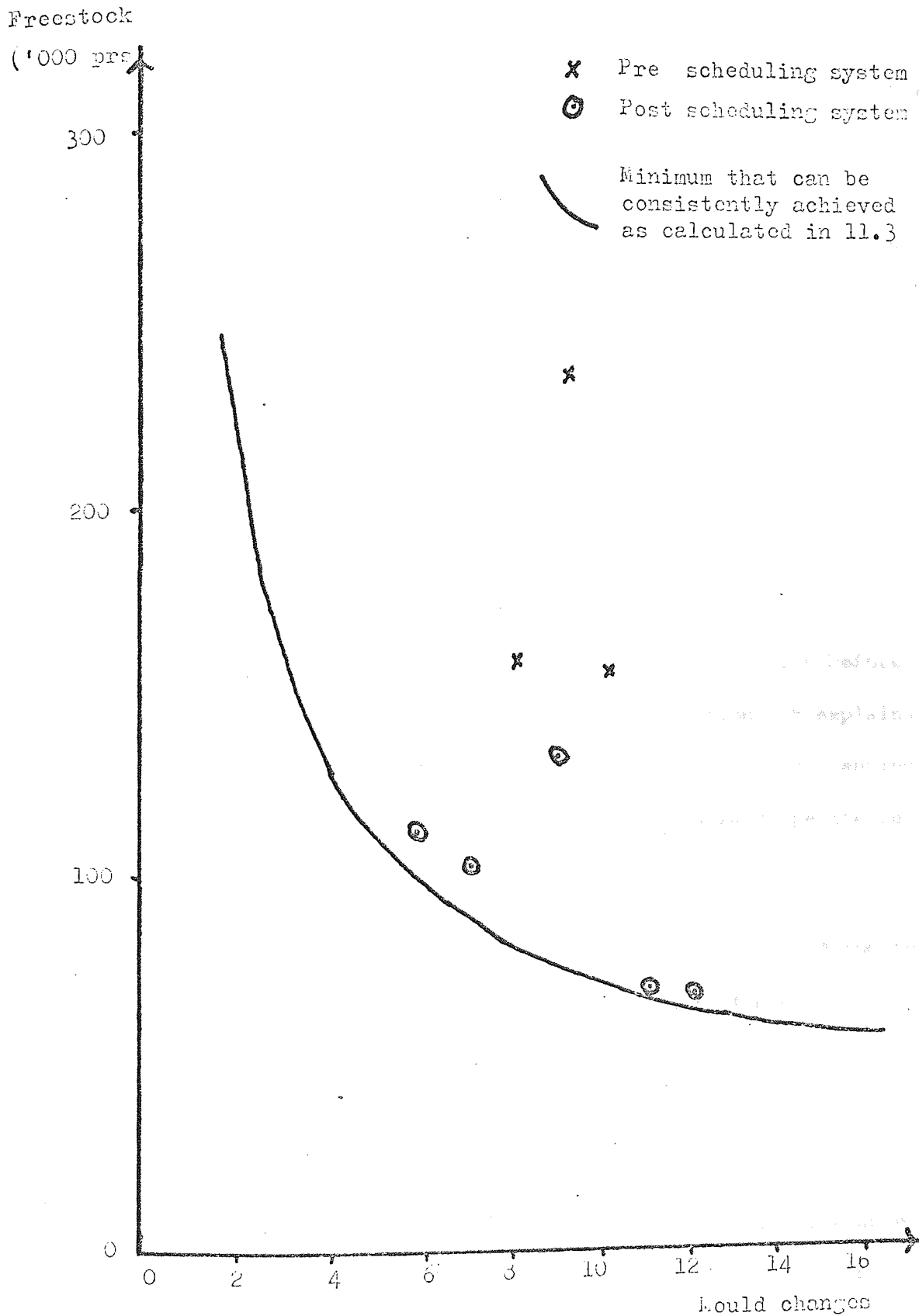


Diagram 16

RELATIONSHIP BETWEEN THE FREESTOCK AND MONTHLY  
MOULD CHANGING ON THE LARGE PROTECTIVE MACHINES  
ON EIGHT LINES BETWEEN OCTOBER 1972 AND 1975



CHAPTER 8    INJECTION MOULDING AND ITS EFFECT ON  
PRODUCTION PLANNING

8.1    Introduction

The main purpose of this chapter is to establish the major controllable factors affecting the output from a machine. This is done in two ways; by a theoretical study of the process in sections 8.2 to 8.4 and by a statistical analysis of the output figures over several months (see 8.7). The results are in general agreement (see 8.8) and yield few dramatic conclusions for production planners.

In detail, section 8.2 describes the injection moulding process. Section 8.3 explains why P.V.C. degrades and how the mould loading can affect the rate of degradation. Section 8.4 examines the factors which control the production rate.

The next two sections consider other effects of the production before returning to the production rate in section 8.7. Section 8.5 explains why schedules are prepared in weekly units to keep down mould changing costs. Section 8.6 shows that machines will almost always operate fully loaded.

Note the use of the word 'template' to mean an individual mould and thus avoid confusion with the meaning of 'mould' as a pair of moulds (see 2.4.2).

8.2    The injection moulding process

Injection moulding involves heating a plastic until it will flow under pressure. It is injected into a mould where it solidifies. The moulded

product is then removed and the mould is prepared for its next injection. See Rubin (19) for a comprehensive guide to 'Injection Moulding'.

The machines used at Dunlop Footwear have a central turntable, two fixed injection barrels with supply hoppers, and a control panel. The turntable has ten stations which hold the moulds for five pairs of shoes, with the right and left templates in adjacent stations. The templates are presented in turn to the injection barrels by rotation of the turntable, the moulding cools at several stations before it is removed. (See diagram 6). The processing of the P.V.C. in the injection barrel is described in the next section.

The control panel allows certain temperatures, pressures, times and volumes to be set. The setting of these controls is discussed briefly in section 8.4.5.

#### 8.2.1 In the injection barrel

(see diagram 17)

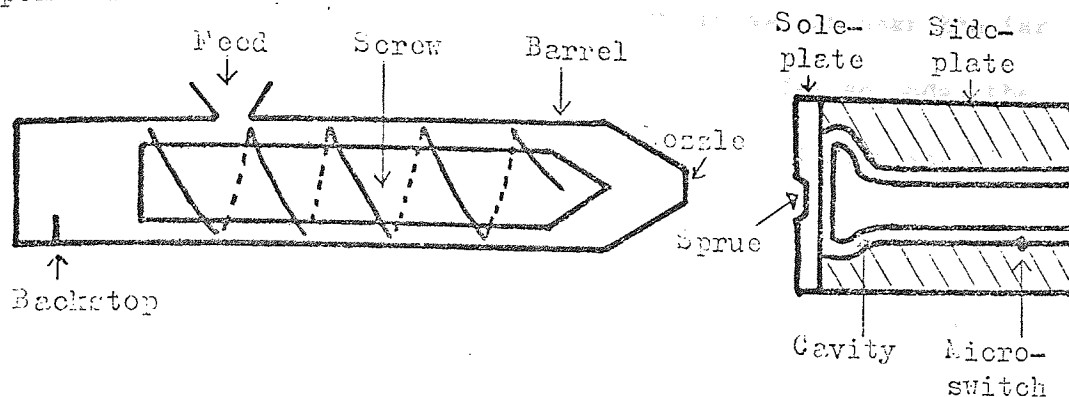
The injection barrel contains an injection screw which is free to rotate and to move forwards and backwards. After each injection, the screw rotates pushing the plastic up the barrel.

The plastic melts primarily through shearing by the screw, but also by conduction from the heated injection barrel. It is molten and well mixed when it reaches the end of the barrel.

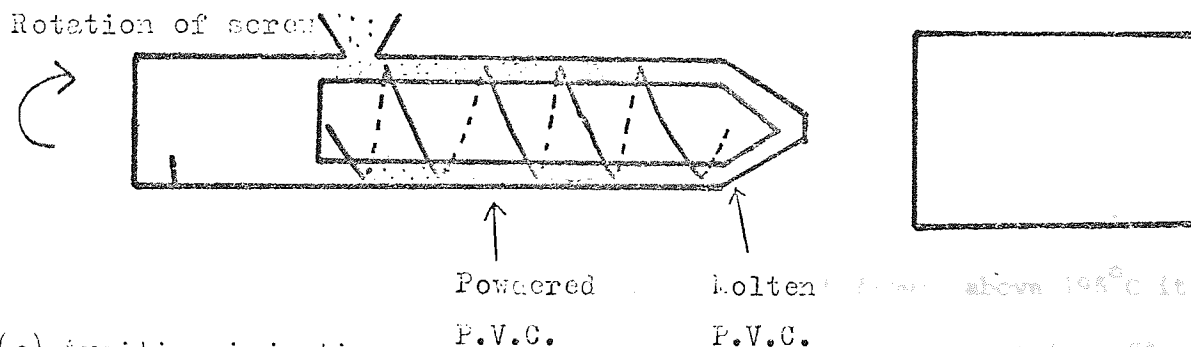
The incoming plastic generates pressure in front of the screw, pushing it back. The screw stops rotating when it reaches a 'backstop' which determines the volume of plastic in front of the screw - the 'shot size'.

When the next template is ready, the barrel moves forward. The nozzle

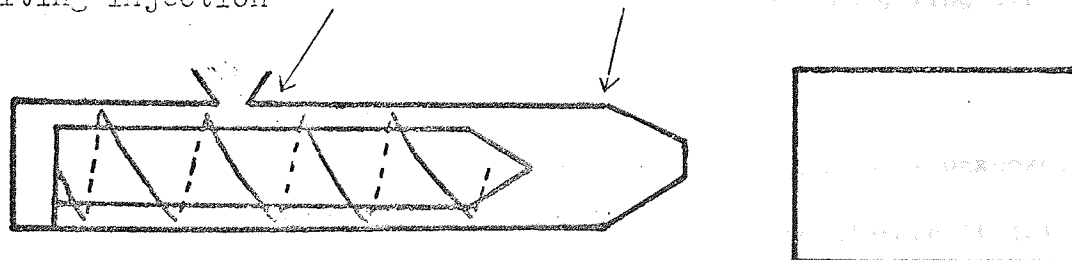
(a) Components



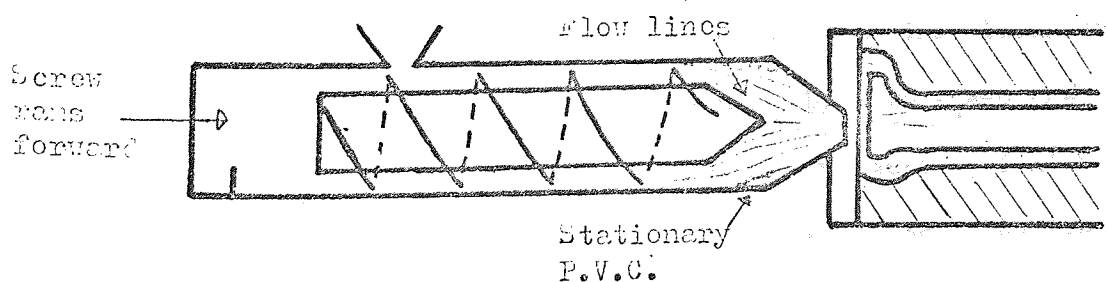
(b) Starting to fill



(c) Awaiting injection



(d) During injection



opens on contact with the injection hole in the sole-plate. The screw rams forward injecting the plastic into the mould under pressure.

The injection stops when plastic reaches a micro-switch near the far end of the template. Pressure is maintained for a few seconds, the 'dwell time', to consolidate the moulding as the cooling plastic contracts, and to prevent a backflow from the template.

### 8.3. Degradation of the P.V.C.

After the above outline of the production process, one wishes to know how the mould loading can affect the output. This section explains how it affects the rate of degradation of the P.V.C.

#### 8.3.1 Introduction

P.V.C. is difficult to mould because it has a restricted range of moulding temperatures. Below  $170^{\circ}\text{C}$  it will not flow; above  $195^{\circ}\text{C}$  it degrades rapidly, weakening the molecules of plastic and giving off HCl gas (20).

Despite many studies the precise mechanism of degradation is unknown. However, continued heating or shearing is known to accelerate it (21,22). There can be considerable local temperature variations of the plastic within the screw (23) so some degradation is generally unavoidable.

Minor degradation is unnoticeable. Further degradation discolours the plastic and is most noticeable on light colours. By this stage the properties of the plastic are slightly affected. The surface finish is blemished by gas bubbles and other moulding marks after excessive degradation.

### 8.3.2 Effects of the mould loading

In a normal screw injector the 'shot size' - the amount of plastic held in front of the screw - is little more than the capacity of the template. Each injection purges the barrel and the P.V.C. has little chance to decompose.

On the newest machine at Dunlop Footwear the shot size can vary from template to template (see 8.3.3); on all other machines it must be set large enough for the largest template. An injection into a smaller template will not purge the barrel. The flow-lines are such that P.V.C. round the edge of the barrel hardly moves and may thus reside there for a long time (see diagram 17d). The amount left in the barrel will depend on the difference in volume between the current template and the largest template in use on the machine.

P.V.C. remaining in the barrel is repeatedly heated and sheared which encourages degradation. This becomes apparent if there is a large difference in volume between the smallest and largest moulds. In such cases degraded P.V.C. left after an injection into a small template is often found in the second template of the pair.

The 'size-mix' cost is the expected value of the lost output associated with a proposed set of five moulds rather than five moulds identical to the largest mould proposed. The highest cost occurs with one large size and four small sizes being moulded. P.V.C. can then remain in the barrel for up to 8 injections with a strong possibility of degradation.

### 8.3.3 Restricting the mould loading

The manufacturer told the company it could mould any set of sizes, together providing it kept small and large templates out of adjacent



stations. During machine testing the company found it could not mould very small and very large sizes together without degradation (see 8.3.2). It therefore restricted the spread of sizes in any machine and found the constraint on adjacent stations had no effect.

The company did not establish the maximum size spread which could safely be run. Instead it found the minimum spread for which scheduling was practicable. It established that there was no observable degradation with this size spread, and forbade the scheduling to exceed this spread.

A new machine, the number 4 large 'protective' machine, has adjustable shot sizes so it is permitted a wider spread of sizes. It is unclear whether this additional feature makes any difference since comparative tests have never been made. In particular it has never been tested with the maximum possible spread of sizes.

#### 8.4 The production rate

Degradation is only one factor affecting the output of 'bests'. This section examines how the production rate depends on controlled variables like the cycle time and mould loading. The basic production rate of the machine is inversely proportional to the 'cycle time'. This is the time taken for the machine to index one station, i.e. a tenth of the revolution time, and is a controlled variable.

Not all the production time is effective since there are breakdowns and adjustments to the machinery. The 'downtime' is the ineffective time, the 'net production rate' is the basic production rate times the fraction of time that is effective.

Some output, including degraded output, is rejected or classified as second quality. The production rate of 'bests' is the net production rate multiplied by the fraction of top quality production.

#### 8.4.1 The cycle time

The cycle time must be sufficient to allow the machine to function smoothly. Three factors may limit it. The operative(s) working the machine must have enough time to remove the finished product from the last and to pull on a new lining. The moulding must cool sufficiently before removal so that it does not subsequently deform. The injection barrel must have enough time to inject and refill.

The machine is designed to take the correct relative times for these operations so they are completed at about the same time. The times are not fixed but depend on the moulds, the formulation of the P.V.C. mix, and the settings of the machine.

#### 8.4.2 Downtime

The major causes of downtime are mechanical and electrical breakdowns, moulding faults, breaks by the operatives to recuperate, and supply problems.

Supply problems increase downtime when the machine is switched off awaiting materials. They are most likely when the schedule has been altered recently, and are part of the cost of such changes. They can be assumed independent of the machine controls.

A short cycle time is likely to increase all other causes of downtime since everything is working a little faster and is more likely to fail. For example, the operatives' breaks depend on the number of operatives assigned to the machine and the effort required, which in turn depends

on the cycle time. They are unlikely to depend directly on other controls.

Breakdowns and moulding faults are particularly likely during a start-up shift before the machine has properly warmed up. They depend on mechanical and human factors and on the quality of the molten P.V.C. As examples, an old or poorly-maintained machine is more likely to break down; a cheap or poorly-adjusted template has more moulding faults; and degraded or poorly mixed plastic makes moulding faults clearer and, by upsetting the machinery, gives more breakdowns.

#### 8.4.3 Quality

The quality is reduced by moulding faults, degraded P.V.C. or poor quality work on the linings. A short cycle time may increase all these faults (the latter since the linings are more likely to be poorly fitted onto the last). In general, factors that increased downtime will reduce the quality.

#### 8.4.4 Effects of the mould loading

Cooling, injecting, refilling and manual tasks should all take longer with larger templates for the same type of product. Thus one would expect a slower cycle time with larger moulds, but see 8.4.5.

Larger templates are also more difficult to fill since the plastic must be injected further up a thin leg section, requiring higher pressures and more critical operating conditions. The P.V.C. is thus less likely to be in an ideal state, so downtime and quality are likely to be worse for larger templates.

Therefore the mould loading will directly reduce the production rate through the largest mould, and indirectly through the effect of the size-mix on degradation which increases downtime and decreases quality.

#### 8.4.5 Setting the controls

Recent company policy has been to set the cycle time as fast as the conditions permit. In a few cases cooling or refilling determine this, but generally the operatives' speed determines the cycle time.

This policy sets the cycle time independently of the mould capacities, accepting higher downtime on the larger moulds as a side effect (see 8.4.2). In practice the cycle times are larger for large moulds because the fitters increase cycle times to cure machine or moulding faults.

The settings for the other controls are found more by trial and error than by theory. The settings may depend on the manufacturer who supplied the P.V.C. as different grades of P.V.C. need different control settings.

Experienced fitters make the best adjustments. Optimising the machine settings demands experience not theory, and is outside my project. I assume only that current performance levels are maintained. I satisfied myself that improvements in setting the controls would not change the conclusions of this chapter although they would affect results.

#### 8.5 Weekly scheduling

The early sections of this chapter concerned the factors controlling the output of 'bests'. Before returning to this subject, the next two

sections cover other aspects of the production process. This section explains why a weekly planning unit was chosen; section 8.6 relates why the machines almost always run fully loaded.

It was standard practice when I arrived to perform mould changes on 'protective' machines at weekends, and on 'canvas' machines during the week. Table 5 based on available cost and production data confirms that this is sound practice. Weekend adjustments are generally cheaper, although paid at overtime rates, because the operatives' time is not wasted. It is rarely worth starting up another machine during a mid-week change because of the high downtime on start-up (see 8.4.2), which would tie up more fitters.

Canvas machines are an exception because most types of 'canvas' mould need adjustment after insertion. This is best done when the machine is running normally rather than on Monday morning while it is warming up. A further disadvantage of weekend changes on canvas machines is that, if several moulds are replaced, while one mould is being adjusted others may produce rejects.

Current practice is further justified by fitters' availability. During the week they stand by for repairs; a long job can only be done during the day, when extra fitters are on, and will seriously reduce the safety cover.

Routine maintenance is done at weekends, together with mould changing and screw-cleaning. A complete machine change can just be done in a weekend, but large numbers of mould changes are inadvisable since they prevent routine maintenance.

Table 5 Comparison of midweek and weekend scheduling costs

Operation	M/C	Time of week	Fitters Hrs. (Menhrs.)	Optv's Hrs.	Spue (lb.)	Scrap Prs.	Direct Cost (£)	Prodn. Hrs. lost
Mould	Canvas	w/e	2 x $1\frac{1}{4}$	2 x $\frac{3}{4}$	3	15	10.60	$3\frac{3}{4}$
Change								
	Small	m/w	2 x $\frac{3}{4}$	2 x $\frac{3}{4}$	5	3	5.00	$3\frac{3}{4}$
		w/e	2 x $1\frac{1}{4}$	-	-	-	6.60	-
	Prot.	m/w	2 x $1\frac{1}{4}$	2 x $1\frac{1}{4}$	5	1	8.80	$1\frac{1}{2}$
	Med.	w/e	2 x 2	-	-	-	8.80	-
	Prot.	m/w	2 x 2	2 x $2\frac{1}{4}$	10	2	11.70	$2\frac{1}{4}$
	Large	w/e	2 x $2\frac{1}{4}$	-	-	-	11.00	-
	Prot.	m/w	2 x $2\frac{1}{4}$	3 x 3	15	4	19.00	3
Flushing	Canvas	w/e	2 x $\frac{1}{4}$	-	8	-	2.60	-
Barrel	& Med.Pr.	m/w	2 x $\frac{1}{4}$	2 x $\frac{1}{4}$	8	2	3.50	$2\frac{2}{3}$
Screw	Canvas	w/e	2 x 3	-	10	-	14.00	-
Clean	& Med.Pr.	m/w	2 x 3	2 x $3\frac{1}{2}$	10	-	16.50	$3\frac{1}{2}$

Other costs for flushing the barrel and for a screw clean are similar.

Note these are not current prices.

#### 8.5.1 The scheduling period

With realistic valuation of production time, mid-week adjustments to the protective machines should be avoided. Scheduling is therefore done in weekly units.

Even if the full weekly output has not been obtained, the planned weekend changes are performed, unless there is a full week's shortfall. This means that batch times not batch quantities are fixed by the scheduling.

Midweek changes are only performed when less than a week's production from a mould is required. Normally only class two manufacturing groups (7.6.1) require such short runs; they are planned in daily units since there are no spare fitters at night.

Although adjustments to the 'canvas' machines are normally made during the week, it is still convenient to plan in weekly units. However, shorter periods can be scheduled as appropriate. Furthermore, the whole programme can be moved back a few days if necessary.

#### 8.6 Unusual circumstances

The machines generally run fully loaded with each mould used on each revolution. There is rarely an advantage in operating otherwise.

Possible exceptions are to match up odd boots, and to maximise output from one mould by running the machine faster and partly empty.

Odd boots are paired up by switching off one mould of the pair for an appropriate number of revolutions. There are never enough 'odds' to make it worthwhile to load unpaired moulds together.



#### 8.6.1 Maximising output of one size

It is occasionally desirable to maximise the output of one particular size, for example to meet an unusual order. It is only appropriate to purchase an extra mould if the normal demand is high (see 12.3). As there are only one or two moulds for each size, their total output may be insufficient, therefore the machine must either run faster or work longer hours.

Machines normally operate five days a week, three shifts a day (see 1.7.1), with maintenance at the weekend. Overtime is possible, but only for one shift a day at the weekend. This action prevents mould changing and routine maintenance, so it is of limited benefit.

An attractive policy if few sizes are needed and others would be surplus to requirements is to run a machine partly empty. Such a machine would require less effort from the operatives so could run faster.

Any increase in speed is limited by the cooling time the moulds need, and by the injection and refill time. The cycle time is set, so it takes the same time to process a vacant mould as one in use. If two adjacent moulds are in use, as they must be if the machine is over half full, the barrel must inject and refill in the cycle time.

A disadvantage of partly filled machines is that some P.V.C. resides much longer in the barrel, despite the higher speed, so that it degrades more (see 8.3). With light moulding colours, discolouring is visible if the machine is run 80% full.

Thus, slight increases in output of one size can be obtained from weekend overtime and from operating partly full machines. The latter

action is rarely worthwhile since the total output will be well down.

## 8.7 Analysis of the output statistics

The early sections of this chapter showed that the output from a machine may depend on its mould loading, which is determined within the production planning system. The objectives of the latter depend in part on the production rate, so it is important to understand the effects of mould loading on this.

This section examines statistically how the production rate depends on controllable factors such as the mould loading, and extraneous factors such as the time of week. Although the results here are specifically required for the production planning system, they also have some value to the management. Note that, due to the high value of lost output, the figures collected here cover only normal size-mixes.

### 8.7.1 Source of information

The factory does not record the production rate of 'bests'. It does however record the net production rate and most other major controlled and uncontrolled variables for each shift and each machine.

The despatches of bests from the finishing department are recorded on a daily basis. Unfortunately this department does not process footwear at a constant rate, so the production rate cannot be linked directly to despatches, although they can reasonably be compared over a month or so.

The cycle time and downtime are measured from a shift log which records at each injection. The shift output is recorded by the operatives. These cross-check to estimate the error in these figures.

### 8.7.2 The set of variables

The variable to be predicted is the true production rate of bests. This cannot be obtained directly so it is calculated as the net production rate (see 8.4) minus the output rates of rejects and second quality products.

The variables controlled by the production planners are the manufacturing group, the mould loading, the moulding colour and the machine used. The moulding colour has an effect on the cycle time which is frequently longer for lighter colours, so the cycle time is partially controlled by the planners although most of its variation is due to random adjustments by the fitters.

Extraneous variables which I expected to affect the production rate are the age and general condition of the machinery, the number of men working each machine since the machine is switched off for breaks if the gang is incomplete, and whether the current shift is a start-up shift. These variables were all included in the analyses, but factors such as supply problems were not.

I expected the mould loading to show its effect in two ways, firstly through the largest mould used, and secondly through the size-mix. It was unclear how to represent the size-mix by a single measure so a wide variety of measures related to the capacities of each mould were used. Some unrealistic measures were tried as controls in the hope that there would be significant differences between the effectiveness of good and poor measures.

### 8.7.3 Hypotheses to be tested

1. The true and net production rates are closely related and vary

inversely to the downtime and cycle time (to a lesser extent). Note that the net production rate equals the effective time (not downtime) divided by the cycle time, thus proving part of this hypothesis.

2. The downtime and the numbers of rejects and second quality products are highly correlated, so that the latter can be predicted from the former.
3. The downtime increases with the largest mould in the machine, some measure of the 'size-mix', and the age of the machinery. In addition it is higher in a start-up shift or with an incomplete gang. Correspondingly the production rate will decrease with all these variables.
4. The downtime decreases if the cycle time is raised while other factors remain unaltered.
5. The cycle time, although controlled, will generally be higher the larger the largest mould in use.

#### 8.7.4 The relationships between downtime, rejects and seconds

The differences between the output of 'bests' and the booked output are due to reject and second quality pairs and overbooking by operatives. The latter was estimated by comparing the total despatches plus rejects with the booked output over a nine-week period.

The downtime, and numbers of seconds and rejects are recorded for each week totalled over all machines. These figures are highly correlated (correlations for a year over .75 which is highly significant), which confirms the second hypothesis that quality and

downtime depend on similar factors. I therefore use the predictor of downtime (given later in 8.7.9) to predict rejects and seconds also. Over several weeks these predictions are reliable not only over all machines but also in individual instances.

#### 8.7.5 The initial analysis

An initial analysis of the data revealed that the output rates varied from one manufacturing group to another. Within a manufacturing group the results were consistent with the hypothesis that the largest size in the machine affects the output. An alternative hypothesis - that the output depended only on the machine age - was also tenable.

There were no detectable mould loading effects for manufacturing groups with only a limited range of sizes. Detailed analysis was therefore restricted to those groups with wide size-ranges, namely the major manufacturing group on the large protective machines and most groups on the canvas machines.

#### 8.7.6 Data collected for the major analyses

The data was gathered over the period from October 1972 to June 1973 from each injection moulding machine. The following variables were recorded for each shift; the claimed production, hours worked, downtime, cycle time, number of men in the gang, and the five mould sizes in the machine. Each piece of data was identified by the shift, day, week and machine.

Incomplete sets of data or data from shifts when a non-standard product was being made were omitted from the analyses.

### 8.7.7 The detailed analyses

(see appendix 1 for further details)

#### 8.7.7.1 Transformation of the data

Three sets of data were used. Two sets related to the major manufacturing group on the large protective machines. The first set was analysed in detail by shift, the second by week since greater detail was no longer needed. The third set of data for the 'canvas' machines was also summarised by week.

Production and downtime for short shifts were scaled up to the equivalent values for full shifts. In addition, a correction was made for running a machine one man short once this had been calculated.

#### 8.7.7.2 Analyses

The first set of data was analysed to determine the increase in downtime for incomplete gangs. All data was then adjusted for this.

The shifts were divided into normal shifts, short shifts and start-up shifts. The production rate in start-up shifts was significantly lower than for other shifts, but since each week contains one start-up no correction was made.

The data was then analysed to determine the effects of machine loading and machine age on the production cycle time and downtime. These effects could not be reliably separated since each machine tended to have its own set of moulds.

Various predictions of the dependent variables were obtained. These were tested on the second set of data; as a result the most suitable

predictors were accepted. Examination of subsequent results show that these predictors are reliable.

Similar analyses were performed for the canvas machines except for the analyses of shift effects. No interesting results were obtained so a further set of data was not required.

#### 8.7.8 Results independent of the production planning

##### 8.7.8.1 The major protective group

The average output from a full week of 15 shifts is 7300 pairs of protective boots, of which 620 on average are rejects or second quality. The standard deviation of the production rate is 900 pairs a week. (This is a statistical measure with the property that a variation of two standard deviations either high or low is exceeded approximately one time in ten).

In a start-up shift the average production is 90 pairs below normal because of increased downtime. The output falls by 70 pairs per machine per shift for gangs which are one man short; this figure is well below the value expected based upon the time allowed for breaks but this is probably due in part to incorrect recording in the log-books.

There are random variations in the output rate which must be independent of mould loading since they occur while it is unaltered. These variations are significantly larger in the long term than the short term, suggesting that there are slow variations in the machine efficiency, so that it has good and bad spells. The variations average 400 pairs per week.



There are very significant differences between the production rates from each machine. These could arise from differences between the machines or from effects of the mould loading since each machine tends to hold moulds of similar capacity all the time (to reduce the size-mix). Such differences cannot be due solely to machine age since a new machine does poorly, but as section 8.7.9.1 indicates, machine age may have a contributory effect.

#### 8.7.8.2 The canvas machines

The data for the canvas machines was not examined in such great detail as that for the protective machines because the mould loading was not found to have any significant effect on the output rate.

The average output for a full week is 9200 pairs of canvas shoes; of these about 600 are rejects or second quality. The standard deviation of the production rate is again 900 pairs per week. (The similarity appears to be coincidental.)

It was impossible to isolate the effects of manning from those of the cycle time, since when the machines were running faster (for a different manufacturing group) more men were usually present. The minor potential benefits from separating these effects do not justify a controlled experiment to determine the answer.

### 8.7.9 Results related to the production planning

#### 8.7.9.1 The major protective group

To test the hypotheses produced earlier, the first set of data was used to produce predictors of the production rate, downtime and cycle time. These predictors were then tested on the second set of data.

#### 8.7.9.1.1 Effects of machine age and largest mould capacity

The output rates were lowest from the machines making the largest moulds but, in addition to this, seemed slightly lower from the older machines. Two predictors of the production rate were equally good, one of these involves the machine age also.

These are:-

Production rate =  $591 - 109.8 \times \text{Max}$  (in pairs per shift)

Production rate =  $866 - 86.0 \times \text{Max} - 12.8 \times \text{Machine age}$

where Max is the volume of P.V.C. in kgs. held by the largest mould in the machine.

The correlations given by these two predictors are .65 and .64 respectively, both highly significant. The second corresponding predictor of downtime, which was also used to predict numbers of rejects and seconds (see 8.7.4) is:-

Downtime =  $58 \times \text{Max} + 8.1 \times \text{Machine age} - 129$  (minutes per shift)

#### 8.7.9.1.2 Effects of the size-mix

All measures of the size-mix were negatively correlated with the output, as expected. The worst correlations came from deliberately unrealistic measures; the best measures used the logarithms of the P.V.C. volume rather than the actual volumes (which would exaggerate the effects of large moulds).

After correcting the production rate for the effects of the largest mould, as calculated above, the best measure of 'size-mix' was a linear measure involving the sum of differences between the logarithm for the largest mould and for each other mould. This was slightly better than a similar quadratic measure. However

even this measure gave a correlation of only .18 with the production rate, which although significant is very small. Furthermore when tested on the second set of data all predictors including a size-mix effect were significantly worse than those without.

#### 8.7.9.1.3 The cycle time

The cycle time increases with the largest mould as expected from hypothesis 5, but most of its variation is independent of this. The downtime decreases slightly as the cycle time rises (see hypothesis) but the overall effect is to reduce the production rate.

This may be an effect not a cause since the cycle time is increased if the machine is behaving badly; however, it suggests that in general fast cycle times are preferable.

#### 8.7.9.1.4 The new machine

The new machine has adjustable shot sizes for each mould so it may perform differently from the other machines. The average prediction error using the formula given earlier is 41 pairs per shift compared with an error of 37 if the average value is used, therefore it is reasonable to conclude there is a significant difference after allowing for age effects between this machine and older ones and that a wider size-mix can be used on this machine.

#### 8.7.9.2 The canvas machines

The production rate of canvas footwear is almost entirely determined by the cycle time. There are only minor variations in the downtime

and these appear to be independent of the mould loading.

The cycle time depends on the manufacturing group and colour, and to a much smaller extent on the largest mould, but it also varies significantly independently of other known factors. There is no apparent size-mix effect within current practice despite fairly wide size spreads.

## 8.8 Conclusions of this chapter

The results of this chapter are not dramatic. They do not suggest significant new ways of production planning. Their value lies instead in showing where current practice has been appropriate and where it might be altered. The other significant effect is that the production can now be forecast in advance with much greater accuracy than was formerly possible.

### 8.8.1 Effects on production planning

Section 8.5 demonstrated that it was correct to change moulds on the protective machines at weekends and on the canvas machines during the week. Section 8.6 showed that the machines should almost always run fully loaded.

Section 8.3 showed that degradation would make it inadvisable to run a wide mix of sizes together in a machine, but section 8.7 indicated that, within current practice, the size-mix has no significant effect on output. This implies that degradation is not severe at these levels which can therefore be relaxed slightly, but as the size-mix is widened a critical point will be reached at which degradation becomes severe and output falls significantly. Section 8.8.2 describes a cost-model to use in production planning for the size-mix effect.

Section 8.7 showed that the output rate depended on the largest mould and possibly the machine age. The demand determines which products to make so large moulds must be used even if the production rate is lower. The results will not therefore alter the production planning, except that grouping together large moulds (as is already done to restrict the size-mix) will reduce the number of occasions when a large mould must be run.

Note that the analyses gave a higher correlation to the largest mould capacity rather than the mean mould capacity in predicting the production rate; however they were not significantly different. If the latter effect is correct, then grouping together large moulds is unnecessary, since the average production rate would depend solely on the demand and not the mould schedule.

Other factors which affect the output have little interaction with production planning. For example, absenteeism does not occur according to plan although one can specify which machine should lose output if there are absentees. The production planner should examine recent output figures and adjust production to correct stock levels towards their desired values.

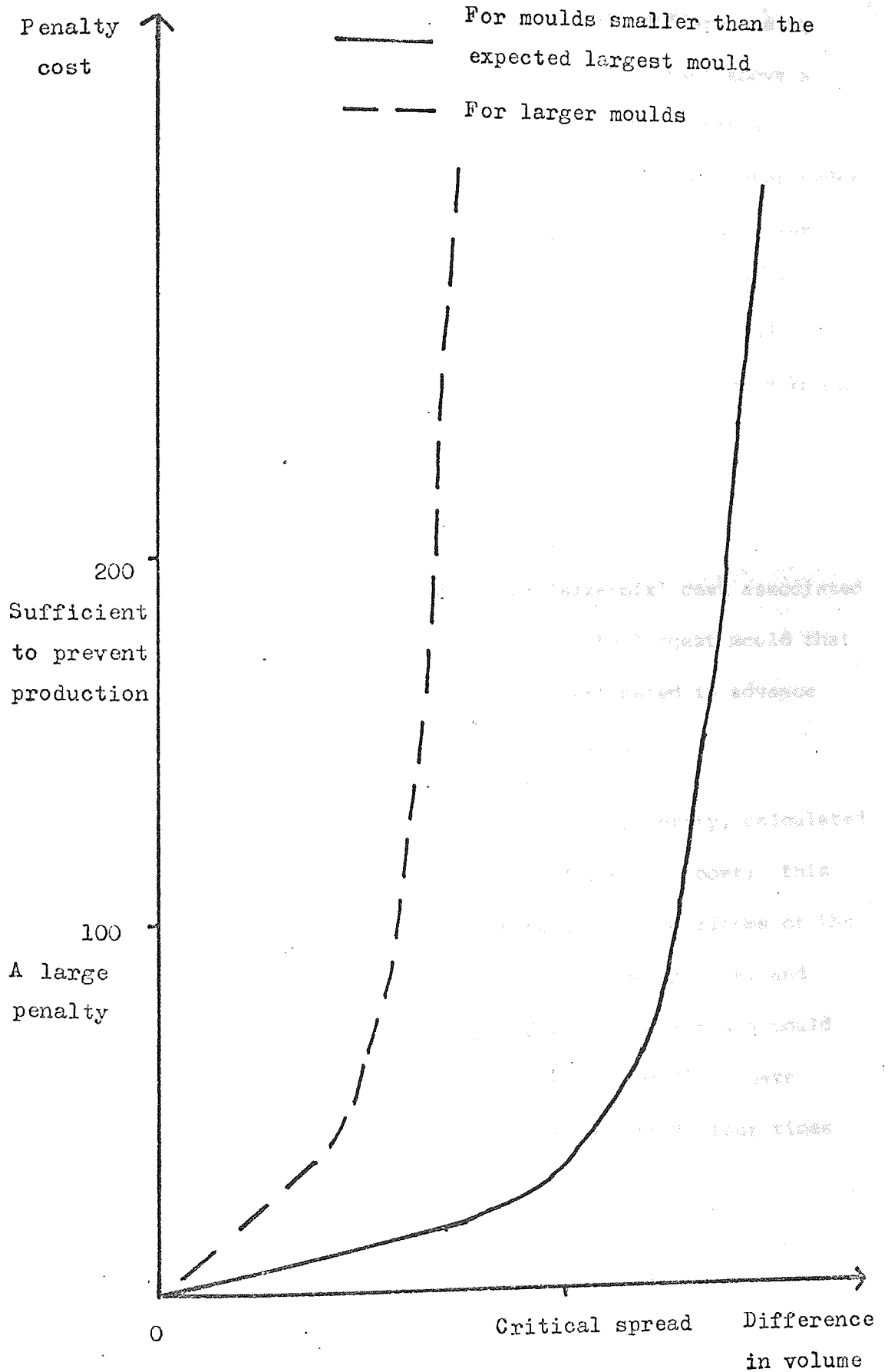
#### 8.8.2 A model of the size-mix costs

As just explained, degradation is not observable as a result of wide mixes of sizes within current practice, but at very large differences the degradation is so severe that production is impractical.

The theoretical study suggests that degradation should depend on the quantity of P.V.C. left in the barrel after each injection. I assume that the effects are additive so that the estimated value of lost

Diagram 18

A TYPICAL GRAPH OF THE  
ESTIMATED 'SIZE MIX' COST



production, the 'size-mix' cost, is the sum of separate components for each mould. This convenient assumption is in agreement with the statistical results (see 8.7.9.1.2).

The 'size-mix' cost for each mould is low for small differences in volume, but rises very rapidly as the difference increases above a critical level. However the statistical analysis shows that a linear effect or no effect at all is more accurate than a higher order effect within current practice. The model I use combines a linear effect which dominates for small spreads, with a very high order (eighth order) effect which dominates above the critical spread (see diagram 18). This type of model is needed to satisfy the facts known about the size-mix cost.

#### 8.8.3 Use of the size-mix cost in mould scheduling

The above section shows how to estimate the 'size-mix' cost associated with running a specific mould. When planning, the largest mould that will be in a machine is unknown but it can be estimated in advance using the previous week's largest mould as a guide.

In deciding whether to run a particular mould the priority, calculated as in 9.5, will be adjusted by the estimated 'size-mix' cost; this is  $kx + (x/c)^8$ , where  $x$  is the difference between the logarithms of the proposed mould and the largest mould expected in the machine, and  $k$  and  $c$  are appropriate constants. If, however, the proposed mould is larger than the largest mould expected, its use will increase the size-mix for all four other moulds so the penalty is four times as large.

9.1    Introduction

The product scheduling solution is described in two chapters. This chapter describes the mould scheduling solution, chapter 10 covers the safety stock solution. Both solutions assume that the machine loading has already been prepared, preferably as in chapter 11, and consider only one manufacturing group at a time.

Both chapters commence with a survey of relevant literature (see 9.2 and 10.2). They proceed with an account of how the appropriate module was designed, and finish by showing how near to the optimum the module is in practice. Details of the improvements on previous performance are given in chapter 15.

Section 9.3 gives a theoretical basis for the scheduling system, while section 9.5 outlines the major changes that must be made to implement this in practice. In contrast, section 9.4 describes an alternative scheduling system which is theoretically better than the proposed system, but which performs worse in practice. Finally section 9.6 gives the results of various practical tests.

A handbook on the product scheduling is provided as appendix 3 and the mould scheduling algorithm has been coded into a computer program which is enclosed as appendix 8. For illustration, diagrams 19 and 20 show parts of a typical machine loading and mould schedule.

9.2    Literature survey on mould scheduling

Dunlop Footwear is a batch manufacturer producing mainly for stock in a process with only one critical stage. Relevant literature concerns batch processing not 'job shops'.



Diagram 19

A POSSIBLE MACHINE LOADING FOR  
THE LARGE PROTECTIVE MACHINES

	Week	1	2	3	4	5	6	7	8	9	10	...
Machine 1		1	1	1	1	1	1	1	1	1	1	
" 2		1	4	4	4	4	4	1	1	1	1	
" 3		1	1	1	3	3	3	3	4	4	1	
" 4		1	1	1	1	1	1	1	1	1	1	

Diagram 20

A POTENTIAL CORRESPONDING MOULD SCHEDULE  
FOR MANUFACTURING GROUP 4

	Week	1	2	3	4	5	6	7	8	9	10	...
<u>Machine 2</u>												
		Men's sizes										
1 <sup>st</sup> mould		7	7	11	11	6						
2 <sup>nd</sup> mould		8	8	8	8	8						
3 <sup>rd</sup> mould		8	8	8	9	9						
4 <sup>th</sup> mould		9	9	9	9	9						
5 <sup>th</sup> mould		10	10	10	10	12						

Machine 3

1 <sup>st</sup> mould	7	11
2 <sup>nd</sup> mould	8	8
3 <sup>rd</sup> mould	9	8
4 <sup>th</sup> mould	9	9
5 <sup>th</sup> mould	10	10

Machines numbers 1 and 4 are not used to produce manufacturing group 4 in this period.

The general batch processing problem is to determine optimal 'batch quantities' and 'safety stocks' for each product to minimise production, inventory and shortage costs for a given set of requirements and subject to specified constraints. In this form, continuous time is assumed.

In contrast, with discrete time periods, the problem can be stated as 'to decide which products to make at any time'. These definitions are equivalent since production commences when the planned stock falls to the 'safety stock' and continues until the 'batch quantity' has been produced.

The latter definition makes it clear that the 'batch quantities' and 'safety stocks' may interact and can vary with time. Nevertheless the interaction is small so most of the literature considers these separately; literature on safety stocks is therefore discussed in section 10.2.

In setting batch quantities the demand is often assumed to be known and the requirements are taken as the cumulative demand plus the safety stocks. Such requirements are called 'scheduling requirements' here.

#### 9.2.1 Batch scheduling by Linear Programming

Linear Programming (L.P.) can be used to solve scheduling problems with linear costs, fixed demand, and constraints expressed as linear equations. The usual variables are the production of each product in each period; the major constraints are that requirements are met (24).

The usual L.P. formulation of the scheduling problem ignores set-up

costs, which form a major part of the variable costs here. One possible alternative is to define a variable for each possible production pattern. If there are no capacity constraints and no costs for varying the production rate, a product needs no initial stock in a period in which it is produced (26). Alternatives in each of  $n$  periods are to produce or not, giving  $2^n$  alternative production patterns for each product. Each pattern has an associated set-up cost. Dzielinski et al. (25) aggregate variables to give a reasonable problem size. They use simulation to conclude that lot size programming is better than an Economic Batch Quantity system in a dynamic uncertain environment.

The neatest solution to this problem with a single product is provided by Wagner and Whitin (26) using Dynamic Programming (see later). With more products, Gilmore and Gomory (27) adopt a two-stage solution using a small separate L.P. problem to identify the next production pattern to include in the solution.

The above method could be adapted for this problem but the size of a realistic model would make it impractical for the company's computer. Furthermore, one would need a simple method of rounding non-integral variables while retaining a good feasible solution. This would not be easy here because of the number of such solutions. The optimal method, Integer Programming, is prohibitively expensive.

#### 9.2.2 Dynamic Programming

A typical problem for which Dynamic Programming is applicable is the minimisation of the expected discounted costs over a finite period. The solution is found by first determining the optimum decision in

the final period for each possible state at the start of that period, and then by progressively considering less remote periods until the optimal current decision is determined (see Bellman (28)). The optimal solution is calculated for each possible future state so the approach is impractical if there are a large number of possible states in each period.

Wagner and Whitin (26) provide a neat solution to the set-up problem for a single product, but it is not generalisable to the constrained multi-product problem.

This problem is too large for a direct approach, but one can use Dynamic Programming to study the form of the optimal solution. Much of the literature quoted in chapter 11, particularly the works by Arrow, Karlin and Scarf, uses this approach, so full discussion of this is left until then.

It should be noted that my approach to mould scheduling in effect uses the Dynamic Programming algorithm with an approximation to the optimal future strategy.

### 9.2.3 The Economic Batch Quantity

The 'Economic Batch Quantity' is the correct amount to produce with a fixed set-up cost, linear storage costs and a known constant demand rate. It is found by equating the marginal set-up cost and marginal storage cost as functions of the batch quantity (29).

With relatively few products to be scheduled in turn on one machine, it is often impossible to schedule the Economic Batch Quantities (EBQ's) because stocks of one product fall to their safety level thus requiring production before another has completed its EBQ.

Many authors therefore recommend a fixed cycle for the products, e.g. (30). Generally each product is made once per cycle although greater flexibility is given by making some products more or less frequently, e.g. (31). Since the best solution is unlikely to be cyclic, this method gives good but not optimal solutions.

All cyclic approaches assume the starting stocks are as required. They therefore depend on fairly stable demand rates, or all cycles would commence with the 'wrong' stocks.

Cox and Jessop (32) provide a good heuristic system for scheduling when demand fluctuates about a known (and possibly varying) level so that a fixed cycle cannot be maintained.

A product starts production when its planned stock falls to its safety level. It continues until it is replaced by another product or the full batch quantity is made.

The authors demonstrate that the batch quantities should be greater than the EBQ's to compensate for stopping runs early. If several machines are available for production, the increase is generally negligible.

#### 9.2.4 Constrained solutions

The preceding solutions are unconstrained, but often the production rate or desired inventory is specified. Lagrangian multipliers can be employed with batch quantity techniques to satisfy such constraints (see 7.4.1). These artificially adjust the costs and so vary the scheduled production. Appropriate values must generally be found graphically or by successive approximation.

The average inventory of a product is proportional to the batch

quantity (ignoring safety stocks) so the inventory can be adjusted by varying the batch quantities (33). The change is only effective when the product is next made, so the actual inventory lags behind its desired value.

Better control is achieved by fixing the production quantity. Instead of determining an appropriate Lagrangian multiplier, Winters (34) uses a priority system to decide what to produce with a similar effect. He schedules products in increasing order of the ratio of actual stock to safety stock until the desired production is reached.

#### 9.2.5 Solutions with variable (stochastic) demand

While demand is almost always unknown, the common solution procedures determine the batch quantities assuming the demand is known. The safety stocks are then set to cover the uncertainty in demand (see 10.2).

Exact solutions can be found in these circumstances, but practical constraints prevent such approaches. Holt et al. (33) specify the problem for batch production, and show that the demand uncertainty has the same effect on batch quantities as increasing the set-up cost. They suggest solution by successive approximations.

Dynamic programming can also be used with stochastic demand, but practical considerations rule out this approach. I have used a similar approach to Holt et al. with slight adjustments to the batch quantities due to variations in demand.

#### 9.3 First steps in the solution

I could not solve the problem (as stated in 5.7) directly, so I reached my solution by considering a simpler problem for which the Economic

Batch Quantity for production (E.B.Q.) is appropriate (see 7.2.2). From this I built up to a full solution.

### 9.3.1 Intermediate problem A

Given a set of  $N$  products with known and constant sales rates

$s_1, s_2, \dots, s_N$ . These products are made in batches at a production rate  $p$ . Each time a new batch is started a mould change costing  $MC$  is required.

Determine a scheduling method which minimises the mould changing cost per period without stockouts and with a given average stock  $K$ .

#### 9.3.1.1 Exact solution to problem A

Simple arithmetic shows that the batch size of each product should remain constant. Let  $A_i$  be the average stock of product  $i$ , and  $B_i$  its batch size.

Introduce a storage cost  $w$  per period into the problem; if at the same time  $wK$  is refunded this does not alter the average costs (since average stock is  $K$ ) so the solution is unaltered.

The ideal batch quantities given by the E.B.Q. formula (7.2.2) are only acceptable if the average stock equals  $K$ . By adjusting  $w$  this can be achieved and the solution to the problem is found.

' $w$ ' is called a Lagrangian multiplier. It is the implicit marginal value of stock due to the constraint on total stock.

#### 9.3.1.2 Mathematical solution to problem A

Basic problem: Minimise  $MC \cdot \sum_i (s_i/B_i)$   
subject to  $\sum_i A_i - K = 0$   
where  $B_i = 2A_i p / (p - s_i)$

Revised problem: Minimise  $MC. (\sum_i S_i (p-s_i) / 2A_i p) + w. (\sum_i A_i - K)$   
subject to  $\sum_i A_i - K = 0$

$$\text{Solution (see 7.2.2)} \quad A_i = \sqrt{\frac{MC. s_i (p-s_i)}{w. 2p}}$$

$$B_i = \sqrt{\frac{MC. 2s_i p}{w (p-s_i)}}$$

$$\text{where } w = (\sum_i \sqrt{s_i (p-s_i)})^2. \frac{MC}{2pK^2}$$

- Note: 1)  $w = MC. s_i / A_i B_i$  for all products  
2) The production costs are inversely proportional to the total stock,  $K$ .

#### 9.3.1.3 Discussion on problem A

This approach combines two common techniques, determining batch quantities with substantial sales rates (e.g. (17)) and meeting a constraint on total inventory (e.g. (33)).

This solution could be extended to include general storage costs. Unless these are constant, as assumed here, an explicit formula for calculating  $w$  does not exist although it can be found graphically (e.g. (33)).

It is unlikely that stocks of one product will fall to zero just as the ideal quantity of another product has been produced. To represent the situation in a factory with a constant production rate one must solve the related problem B.

#### 9.3.2 Problem B

In the context of problem A, assume there are  $L$  mould places. These must all be in use giving a production rate  $Lp$ . Assume this equals



the demand so the total stock remains constant. Find an optimal scheduling method.

#### 9.3.2.1 Background to solutions to problem B

Unless the solution to problem A happens by chance to be feasible for problem B, there are no simple solutions to problem B. Any algorithm yielding optimal schedules is specified in section 9.4. Like most optimal procedures for scheduling problems it includes an extensive search through possible solutions.

Such approaches are costly and time-consuming. Furthermore optimal schedules are very sensitive to the boundary conditions which frequently alter before they are reached.

A common but non-optimal approach uses fixed cycles with each product made once per cycle (e.g. (30)). This procedure avoids clashes between products so is appropriate with only one mould place, few products and stable sales rates. These conditions do not apply in practice. With several mould places, clashes between products are less important while flexibility in the system is more important. I therefore adapted the algorithm for problem A to give an efficient algorithm for problem B.

#### 9.3.2.2 Justification of a priority approach

In problem A the greater the stock of a product, the less worthwhile it is to continue producing it. There is a critical value of  $w$ , the marginal value of stock, such that an optimal scheduling rule is "start production of a product when stocks fall to zero; continue while the marginal value of further stock exceeds  $w$ ".

In problem B, near the scheduling horizon the marginal value of

further production may rise; furthermore changes in the production of one product affect succeeding products so it is difficult to calculate the true marginal value.

Away from the scheduling horizon interactions between products should be small, so the scheduling rule for problem A should be nearly optimal for problem B.

The manufacturing groups which are hardest to schedule are in continuous production so the scheduling horizon is always artificial, and horizon problems have a low importance. I decided to develop an algorithm which scheduled products in order of priority where the priority is an estimate of the marginal value of production.

This approach is similar to that of Cox and Jessop (32). They assume surplus capacity and only start production as necessary, I load to capacity (since the machines behave poorly when partly loaded (see 8.6.1)) thus some products may start production early. In the full problem the priority considers additional factors thus extending their work.

### 9.3.3 The 'priority' algorithm for problem B

The Dynamic Programming approach states that the best action now is the one which, when followed by optimal future decisions, minimises the expected future costs.

The optimal future decisions for problem B are unknown but the solution to the corresponding problem A would be optimal if it were feasible (except near the end of the schedule; see 9.5.7).

The marginal value of production now is calculated assuming that all

future batches are of the ideal batch size,  $B_i$ , given by the solution to problem A. Altering the current batch size will advance or retard future mould changes and use more or less than the average stock. The priority is the expected net gain (or loss) per unit from production now.

The algorithm works by calculating the priority (as below) for each product and scheduling products in order of priority until all mould places are filled. The stocks are then adjusted to reflect the position at the start of the next time period and the priorities are recalculated.

#### 9.3.4 Calculating the priority for problem B

##### 9.3.4.1 Stocks negative or zero

If the stocks in excess of scheduling requirements are negative or zero, the product should be made, so the priority is infinite. (Stockouts are not permitted).

##### 9.3.4.2 Positive stocks, product not being made so mould not in use

This product is not needed until stocks fall to zero. Production now will advance the time of the next mould change and use up extra stock (see diagram 21). Valuing the stock at its marginal value one can calculate the loss from starting production now. Divide this by the production quantity to get the priority of the product.

##### 9.3.4.3 Positive stocks, mould in use at present

Further production will delay the next mould change in proportion to the quantity produced (see diagram 22). It will use more stock if the current stock is above average and vice-versa. There will be a

net gain if the stock is below twice its average value. The priority is the gain per unit production.

Note The priority for a product being made is its marginal priority since the mould can be removed at any time. The priority for a product not being made is an absolute priority and assumes the mould will remain in until stocks are at twice their normal value (when the priority is zero).

### 9.3.5. Mathematics of priority calculation

#### 9.3.5.1 Notation

A	Average stock	(From solution to problem A)	look with
B	Ideal batch size	"	batch
w	Marginal value of stock	"	production
s	Sales rate		
p	Production rate		
U	Stock in excess of scheduling requirements		
P	Quantity to be produced		
MC	Mould changing cost		

From 9.3.1.2  $w = MC \cdot s/AB$

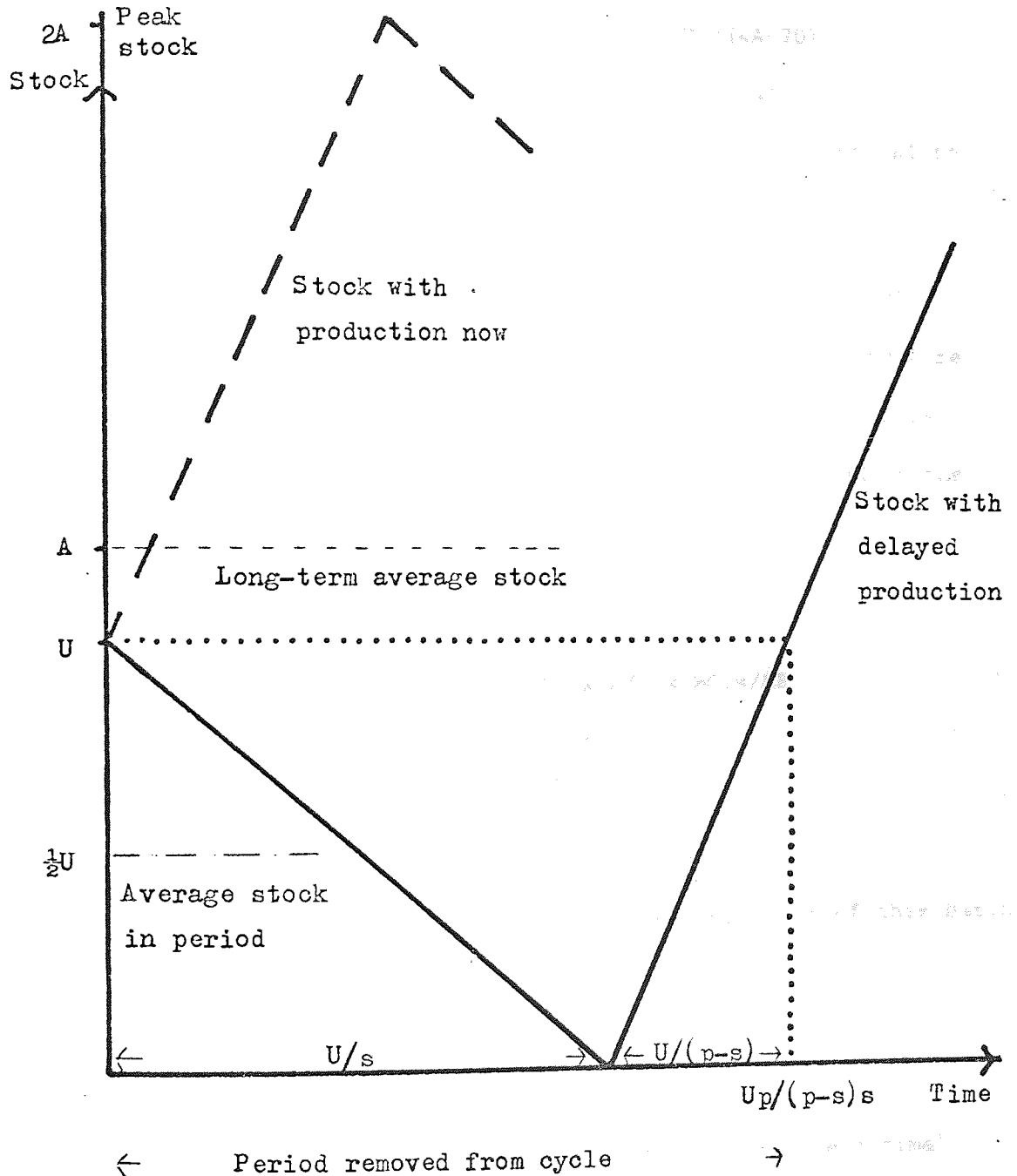
#### 9.3.5.2 Case 1 - Mould not in use at present (see diagram 21)

The mould can remain out of use for a time  $U/s$  before it becomes urgent. It will take a further time  $U/(p-s)$  before the stock reaches  $U$  again. Thus the next mould change would be advanced by time  $Up/s(p-s)$  by production now, at a cost  $MC \times Up/s(p-s) \div (B/s)$  where  $B/s$  is the normal interval between mould changes.

The average stock in the period would have been  $U/2$  instead of the long term average  $A$ . The extra stock required is valued at the marginal value of stock  $w$ . The quantity produced is  $(2A-U) \times p/(p-s)$ .

Diagram 21

THE EFFECT ON STOCKS OF STARTING  
PRODUCTION OF A PRODUCT EARLY



As a result of starting production now rather than at time  $U/s$ , the whole cycle has advanced by a time  $U/(p-s)s$ . The average stock in the period is  $\frac{1}{2}U$  rather than  $A$ .

$$\text{Extra mould changing cost} = MC \times U/p/B(p-s)$$

$$\text{Value of stock used} = (A-U/2) \times (U/p/s(p-s)) \times MC \times s/AB$$

$$\text{Total cost} = MC \cdot U/AB \times p/(p-s) \times (2A-U/2)$$

$$\begin{aligned} \text{Cost per unit produced} &= MC \cdot U/AB \times (4A-U)/(4A-2U) \\ &\text{or } w \cdot U/s \times (4A-U)/(4A-2U) \end{aligned}$$

(Note that for small  $U$  the cost is approximately proportional to the sales cover  $U/s$ ).

#### 9.3.5.3 Case 2 - Mould in use at present (see diagram 22)

Further production of  $P$  will delay the next mould change by time  $p/s$ . Since one need consider only marginal production so  $P$  is small, the average stock in this period will be  $U$  instead of the long term average  $A$ .

$$\text{Saving in mould changes} = MC \cdot x (P/s)/(B/s)$$

$$\text{Value of stock used} = (U-A) \times P/s \times MC \cdot s/AB$$

$$\text{Net gain} = P \cdot MC/AB \times (2A-U)$$

$$\text{Gain per unit produced} = MC/AB \times (2A-U)$$

$$\text{or } w \cdot (2A-U)/s$$

(Note that the gain is proportional to the proportion of this batch still to be made).

#### 9.4 An optimal procedure for problem B

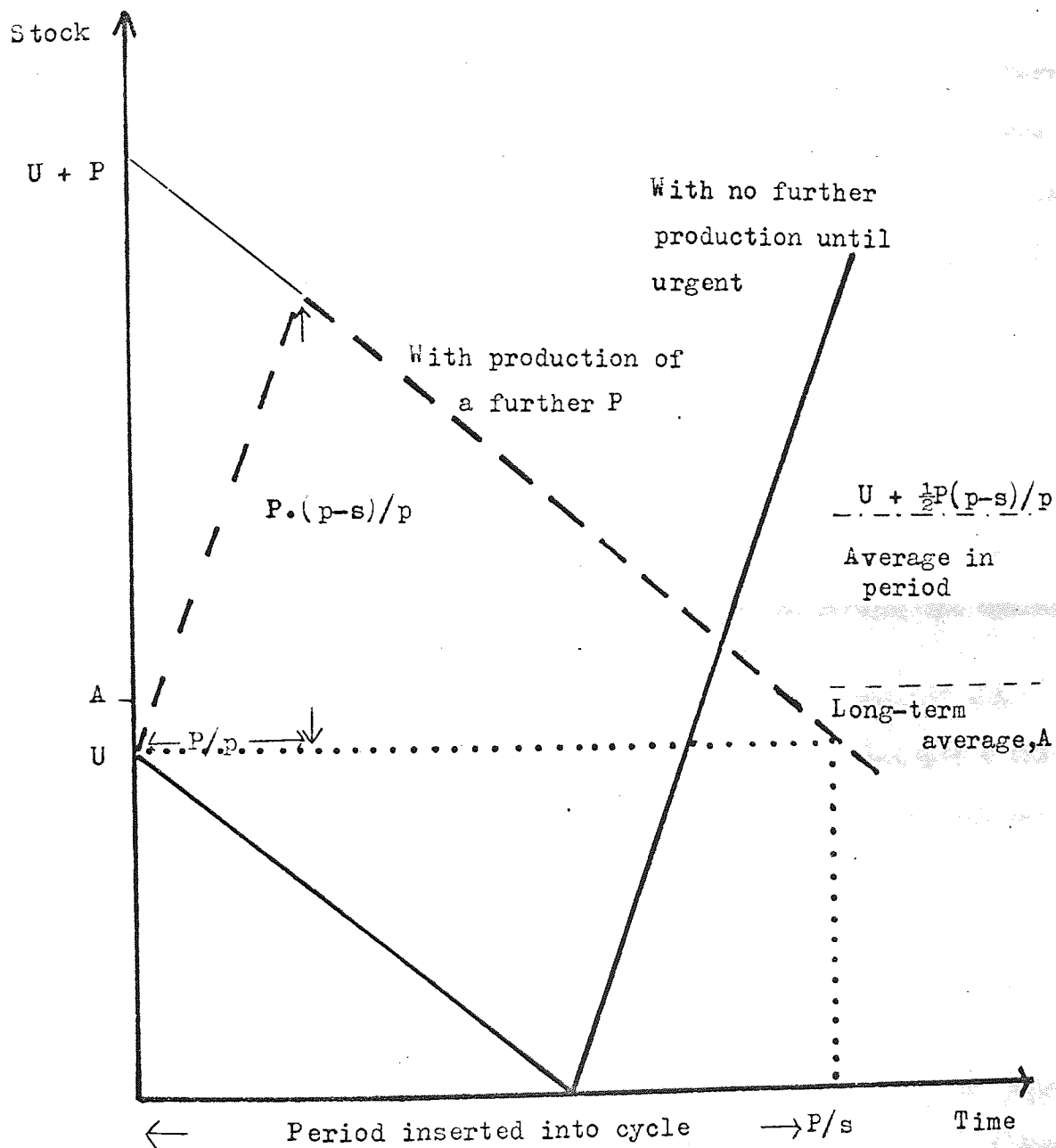
The solution method outlined here was developed to provide optimal solutions to problem B. It proved an excellent method of doing this. However it was very time-consuming, not very flexible and non-optimal when applied in practice (see 9.4.4). It was therefore abandoned although some features were transferred to the priority method.

##### 9.4.1 Problem

To minimise the number of mould changes necessary to meet a given

Diagram 22

THE EFFECT ON STOCKS  
OF CONTINUING PRODUCTION



By continuing production by a further  $P$ , the cycle is delayed by a time  $P/s$ . The average stock in the period is  $U + \frac{1}{2}P(p-s)/p$  rather than  $A$ .

demand with a given production rate while producing in discrete intervals (one week long). The latter constraint was inserted since midweek mould changes are undesirable (see 8.5).

#### 9.4.2 Outline of solution

The demand is translated into discrete terms by specifying the latest times at which each week of each product can be made. A lower bound on the number of mould changes is found. An infeasible solution with this number of mould changes is constructed. This is adjusted until a flexible solution is found or shown not to exist; in the latter case a further mould change is permitted.

#### 9.4.3 Solution

Define  $W_{jk}$  as the  $k^{\text{th}}$  week in which product  $j$  is made, and  $A_{jk}$  as the latest week in which this may be done while satisfying the demand.

The total of all  $A_{jk}$  is fixed by the demand, and the total of all  $W_{jk}$  by the constraint on weekly production. Call the difference the number of 'spares'. Each week early that a product is made uses up a 'spare'.

Step 1 Calculate the latest weeks in which demand can be met ( $A_{jk}$ ).

Define higher  $A_{jk}$  as one greater than the number of weeks.

Step 2 Calculate the totals of  $A_{jk}$  and  $W_{jk}$  and hence the total spares.

Step 3 Produce a table showing, for each product, the maximum number of spares saved for each additional mould change.

Step 4 Find how many spares must be wasted without saving any mould changes through starting earlier than necessary. Subtract from the answer in Step 2.

Step 5 Find  $n$  such that the  $n+1$  smallest values in the table exceed the number of spares. This gives an upper bound for the saving



in mould changes.

Step 6 Mark out a schedule with the minimum number of mould changes.  
Calculate the spares available in each week for this schedule.

Step 7 Eliminate negative values by trying alternative combinations  
of mould changes.

Step 8 Eliminate positive values by re-scheduling whole batches  
earlier.

If steps 7 or 8 are impossible, increase  $n$  by 1 and return to step 6.

A feasible and optimal solution is reached with all values zero.

Occasionally one may abandon a search without showing that it is impossible. In this case the final solution is not proven optimal.

#### 9.4.4 Comments on the solution method

Steps 7 and 8 require the solutions to large integer programming problems. Fortunately one can generally solve these manually by an extensive search method or prove that they are insoluble (if not an unnecessary mould change may be scheduled). Unfortunately it can take two or three days to solve a practical problem manually, while solution by computer would be extremely costly.

This method makes far fewer mould changes than the priority system in the final weeks of a schedule but often has more initially. Since the end date is generally chosen arbitrarily and since rescheduling is generally required before then, this method loses its advantages.

#### 9.5 Solving the full problem

Problems A and B simplify the real problem. They are presented in detail since the solution to the full problem is derived from the 'priority'

algorithm for problem B.

This section discusses how the major differences between problem B and the full problem (redefined below) affect the priority algorithm. Basically the procedure is unaltered. Each mould is given a priority and moulds are scheduled into suitable mould places in order of priority.

#### 9.5.1 Definition of the full problem

(see also 5.7)

Each manufacturing group is scheduled independently; the machine loading states the number of machines, each with five mould places, to use on each group in each period. The scheduling requirements are also specified.

For each period specify:- the colour to run on each machine;  
the moulds to put in each mould-place;  
and the products to output from each mould.

To minimise the sum of:- mould and colour changing costs;  
other production costs related to the spread  
of moulds in a machine;  
appropriate expediting costs;  
and shortage costs if requirements are not met.

#### 9.5.2 Major differences between problem B and the full problem

Table 6 presents the major differences between problem B and the full problem. Specifically the demand is variable; the decisions are made in discrete periods, so some stock is required to cover demand during each period; decisions are made at three levels, colour, mould and product; and additional costs are included in the priority.

Table 6 Major differences between problem B and the real problem

<u>Factor</u>	<u>Problem B</u>	<u>Real problem</u>
Objective	To minimise set-up costs	To minimise production and shortage costs including e.g. expediting costs
Decisions	Made continuously	Made discretely - at weekends
Decision levels	Mould only	Colour, mould and product
Demand	Known and constant	Unknown, varies during the schedule
Production rate	Equals the demand rate	May vary during the schedule
Requirements	Must be satisfied	May be unmet at a cost
Moulds	One product per mould	May be several products per mould
Colours	One	May be several colours
Mould places	Loaded independently	Production costs depend on the five moulds together in a machine
Scheduling horizon	Infinite	Finite or infinite
Marginal value of stock	Constant	Variable

The algorithm also incorporates many minor differences not covered here which do not significantly alter the solution.

In problem B the demand is assumed known so no safety stocks are required. In the full problem safety stocks are added to the expected demand to give the scheduling requirements. Stocks in excess of the scheduling requirements are called 'freestocks', since they are not needed to prevent shortages.

Note that in this section the term 'stock' means 'freestock' and a 'stockout' means dipping into the safety stocks.

### 9.5.3 Effects of the discrete periods

For practical and administrative reasons, mould changes should generally be made only at the end of a period, generally a week long (see 8.5.1). This means that the batch quantities should be multiples of the weekly production  $p$ , with minimum value  $p$ .

#### 9.5.3.1 Minimum stock holdings

If stockouts are forbidden, the minimum stock of a product at the start of a week in which production is necessary is between 0 and  $s$ . At the start of a week following production  $p$ , the minimum possible stock is between  $p-s$  and  $p$ .

In general any value between these extremes is equally likely; the average minimum stock is the average of these values,  $\frac{1}{2}p$ . Thus the minimum possible freestock is half the production per period times the number of products.

Clashes between products prevent operation with this minimum freestock unless occasional short stockouts are allowed. Acceptable schedules

have been produced for freestocks very near to this minimum.

#### 9.5.3.2 Ineffective freestock

Ideally the stock of a product should fall to zero just as production is started. In practice there is generally some stock left, this is 'ineffective freestock'. One wishes to minimise this since it does not reduce costs.

##### 9.5.3.2.1 Calculating the minimum ineffective stock

Assume  $n$  products are made from a particular mould. The mould must restart production at the beginning of the week in which freestocks of any product fall to zero.

At that moment freestocks of other products should be between zero and  $p$  since the basic production quantity is  $p$ . Thus the expected freestocks of other products using that mould is  $\frac{1}{2}(n-1)p$  assuming the freestocks are independent. (In practice they are generally slightly below  $\frac{1}{2}p$  per product but this can be ignored).

Stocks of the critical product run out on average half way through the week, therefore the ineffective stock at the beginning of the week is higher on average by half the sales rate for all  $n$  products.

Adding this over all moulds:-

The minimum ineffective stock equals half the weekly requirements plus (number of products-number of moulds)  $\times$  half the production rate.

Note that the figure given earlier for minimum stock holdings includes this ineffective freestock plus some effective stock.

These calculations assume all products are made in full week runs.

If the rare half-week run became the norm, this ineffective freestock would be halved.

#### 9.5.3.3 Ineffective 'colour freestocks' (with more than one colour)

Just as stocks remain of each product when a mould starts production, so there will usually be stocks left of a colour when switching to it.

To avoid a 'stockout', production must start in the first week during which stocks of any product of that colour fall to zero. On average the balanced stock on commencing production will be (at least) half the weekly sales rate of that colour. The total 'ineffective colour freestock' is half the weekly requirements.

For each colour one size will have no stock when the balanced stock is exhausted (by definition), the corresponding mould will have no excess ineffective stock of half its sales. This slight saving balances the increased ineffective stock due to clashes between colours, so the preceding estimates are used in practice.

#### 9.5.4 Discrete batch quantities

In addition to the ineffective stock holding, weekend mould changing increases the production costs since batch quantities are rounded away from their optimal values.

#### 9.5.4.1 Notation

$Q^*$	Ideal batch quantity (from solution to problem A)
$Q$	Proposed batch quantity (nearer of $r p$ and $(r+1)p$ )
$C$	Storage cost for quantity $Q^*$
$r$	Integral part of $Q^*/p$
$x$	Greater of $Q/Q^*$ and $Q^*/Q$ (so $\geq 1$ )

#### 9.5.4.2 Increased costs from production in discrete units

At the ideal batch quantity the storage cost and mould changing cost per week are equal (see 7.2); the total cost will be  $2C$ .

At the proposed batch quantity  $Q$ , the storage cost is  $C Q/Q^*$  and the mould changing cost is  $C Q^*/Q$ , so the total cost is  $C(x + 1/x)$ .

The ratio of costs at  $Q$  to  $Q^*$  is  $\frac{C(x + 1/x)}{2C}$  or  $\frac{x^2 + 1}{2x}$  which increases as  $x$  increases.  $Q^*$  is between  $r p$  and  $(r + 1)p$  so  $x$  is below  $\frac{2r+1}{2r}$  and the increase in costs is below  $\frac{1}{4r^2 + 2r}$ . Assuming all values between  $r p$  and  $(r+1)p$  are equally likely, the average increase in costs is below  $\frac{1}{12r^2}$ .

With a weighted average batch size of only  $2\frac{1}{2}$  weeks, mould changing costs increase by 2% as a result of discrete batch quantities.

#### 9.5.4.3 Midweek mould changes

For products with very low demand rates mid-week mould changing may be worthwhile despite its increased cost. Let  $K^2$  be the ratio of these costs.

The optimal batch size with a midweek mould change will be  $K.Q^*$ .

(It increases because of the increased mould changing cost.) The

weekly cost is then  $C.KQ^*/Q^* + K^2.CQ^*/KQ^*$ , i.e.  $2KC$ .

A midweek mould change is worthwhile if  $2KC < C(x + 1/x)$ . For the protective machines  $K^2 \approx 1.4$ , so midweek changes are worthwhile if  $x > 1.8$ , i.e. if the optimal batch size  $Q^*$  is below  $p/1.8 \approx 0.55p$ . The scheduling rule adopted allows midweek changes if  $Q^*$  is below  $\frac{1}{2}p$ .

Note: If  $Q^*$  exceeds  $p$ ,  $x$  cannot exceed 1.8, so in particular 1½ week runs are never optimal.

#### 9.5.5 Three level scheduling - colour, mould and product

Three levels of decision making are involved in the full problem. This gives an enormous combinatorial problem if they are considered simultaneously.

In practice, for each week, the colour to mould on each machine is decided first. Then, for each mould, one determines the product that would be made if the mould were run; the priority of the mould is calculated from the urgency of this product. Finally the moulds and associated products are scheduled in order of priority.

The freestock permits the products to be made in batches. It can be divided into a 'colour freestock', which permits batches of each colour, 'size freestock', which permits batches from each mould, and 'range freestock', which permits one to restrict the range of sizes in production (see 9.5.6).

##### 9.5.5.1 Determining the colour to mould

The colour to be moulded may be predetermined. This is particularly likely for class two manufacturing groups where the lighter colours are run first.

Otherwise the 'colour freestock' is used to save colour changes. The



balanced stock of each colour is calculated; the sales cover for the current colour is adjusted for the 'colour freestock'; and the colour with the lowest sales cover is scheduled.

This is equivalent to the algorithm used for mould scheduling. It can be non-optimal, e.g. if a further week's production would avoid further production of this colour for many weeks. Such rare occurrences cannot be avoided without a feedback loop which is too costly; the algorithm performs well in practice.

#### 9.5.5.2 Brand differences

It is possible to obtain a variety of products of one colour from some moulds merely by changing the lining and/or soleplate. This cost is negligible in comparison with a mould change, so products using the same mould are planned jointly.

The next product to be made from a mould is the one with the lowest sales cover; it will run for a week or, rarely, half a week. The priority of the mould is calculated as if there were a single product with that sales cover selling at the aggregate sales rate.

This again may not be optimal. It is the best that can be achieved without full feedback and is quick and efficient.

#### 9.5.6 Adjusting the priority for additional costs

The priority measures the gain or loss in future mould changes from running a particular mould now. The logic applies equally to any other gain or loss, so it can be applied to expediting costs or to the costs of running a wide range of sizes (see 8.8.2). Herein lies the great flexibility of the priority system.

#### 9.5.6.1 Time dependent costs - expediting

Time dependent costs imply it is easier to produce at one time than another; they are almost always associated with supply problems which become easier as time proceeds. Such costs normally commence high, or even infinite, and fall to a constant value which can be taken as zero (since a constant additional cost must be incurred eventually if the scheduling requirements are to be met).

In considering whether to manufacture this week or later the loss can be calculated as the difference in cost in the two weeks, if the latter week is known. In practice the latter cost will be much less than the current cost and can be taken as zero.

Strictly one should compare the optimal strategy following production now with the optimal strategy without production now. This policy would be uneconomic and in practice would rarely change the decision.

Expediting is represented in the model by specifying the material availability for each brand and size and by giving an expediting cost for each week. This is subtracted from the priority if the material available is zero or negative and represents the extra cost of obtaining such material.

The expediting cost can be used as a control variable since, by setting it to a high value, one can prevent production of unwanted products.

#### 9.5.6.2 Restricting the size-mix

As explained in section 8.3.2 it is desirable to restrict the mix of moulds in production together in one machine. The machine is set ideally for one mould, the 'ideal' mould, and the cost of running

another mould depends on the difference in volumes between the moulds. The exact cost assumed is given in section 8.8.2; it contains a linear cost for small differences plus a sharp cut-off cost.

Whenever a particular size is made there will be some cost for running it; this cost will generally be greater for extreme sizes. To avoid a bias against extreme sizes, the priority adjustment equals the expected cost of production now minus the average cost of production of that size.

#### 9.5.6.2.1 Estimation of the 'ideal' mould

We do not know the ideal mould until the machine has been scheduled. To produce a perfect solution one would iterate the calculation until a convergent solution is obtained. This is too costly here so a separate calculation estimates the ideal mould.

Moulds generally remain in use for longer than one planning period, so the ideal moulds in adjacent weeks are related. If several machines are in use, each machine can have its own size range, and the ideal mould for each machine can remain constant.

With only one machine in use, the ideal mould is assumed to move towards the mould most urgently required, so that it increases for several weeks running and then decreases for a like period giving a 'snake-like' appearance to the schedule.

#### 9.5.6.2.2 The average cost of production from a mould

Past schedules were examined to see the normal cost associated with producing each size. In general the difference between the actual

mould and the ideal mould during production was half the difference between the actual mould and the middle-sized mould. The average cost is estimated on this basis.

#### 9.5.6.2.3 Ineffective stock due to restriction of the size range

If the size range is restricted only a fraction of the sizes are admissible for production in any week. The remainder must wait until the next week. Hence these sizes must have one week's stock in hand as an ineffective freestock to be added to the earlier ineffective freestocks.

#### 9.5.7 Near the scheduling horizon

The algorithm in problem B assumes that the horizon is infinite. Near the end of a schedule it can lead to introducing an unnecessary mould, particularly in the final week of the schedule.

The scheduling algorithm has therefore been altered for moulds in use near the end of the schedule; the priority of moulds not in a machine is unaltered. (Near in this case means that each mould should only be used once in the remaining period). The approach is derived from the procedure described in section 9.4.

##### 9.5.7.1 Estimating the gain from further production

The gain from further production now depends on the number of mould weeks still required from this mould. If only one more week is needed, a whole mould change can be saved.

The options considered following production now are either to complete production of everything now, or to stop after this one week and make everything in the next batch.

In the first case the gain is estimated as the mould changing cost divided by the number of remaining weeks. In the second case one gains by delaying the next mould change by a few weeks; the gain is estimated as the saving in implied storage costs.

The cost of further production now is the implied storage cost of that product until it would otherwise have been produced. The priority is then calculated in the normal manner using these gains and losses.

#### 9.5.8 Changes in the priority calculation

Some changes in the priority calculation from problem B (see 9.3.5) have already been described, e.g. the additional costs. However there are some changes to improve the scheduling performance. These are described below.

##### 9.5.8.1 Stock shortages

Some stock shortages are unavoidable, e.g. if there is no material available, so the priority should be finite. It is desirable that it should increase for larger shortfalls or if the mould is currently in use.

The priority during a stock shortage is therefore a large positive value plus increments based on the degree of shortfall and the mould status.

##### 9.5.8.2 High usage moulds

The basic scheduling algorithm performs poorly in practice for moulds with high sales rates (near the production rate). These moulds should have long production runs but they were often scheduled for short runs.

Two factors contribute to these short runs; both relate to the low average freestock for such moulds implied by the E.B.Q. formula. Firstly fluctuations in the demand rate for such sizes can exceed the average stock. Thus on one schedule a mould may be urgent and a duplicate used to increase stocks; on rescheduling, due to low demand, no moulds may be required.

Secondly the marginal value of stock may fluctuate from its average value over the scheduling horizon. If the current marginal value is high, the cut-off priority is well above zero. This biases against high usage moulds since the maximum marginal gains and losses for such moulds are both small. By underestimating the true gain for such a mould, it will not be scheduled.

#### 9.5.8.2.1 Adjustment to the production rate

The actual sales rates for high usage moulds can vary 10% either way from their estimated values. The proposed system overestimates the production rate by 10% in calculating the ideal average stock, thus allowing higher stocks for such moulds to cover periods of low sales rates.

This improves the safety cover (see 10.2.5) and increases the average batch quantity for high usage moulds without significantly affecting other moulds.

#### 9.5.8.2.2 Calculating the priority

The proposed priority for moulds for which the gain exceeds the loss is calculated as the net gain per unit stored per week. This makes the most efficient use of stock in periods while it is in short supply. In particular it aids high usage moulds.

The priority is still taken as the difference between the gain and loss if the loss exceeds the gain. Thus, if the cut-off priority is positive indicating below-normal availability of stock, moulds are selected to maximise the gain per unit stored. If the cut-off priority is negative so ample stock is available, the final moulds are selected to minimise the loss per mould place. At such times the balanced stocks increase and the safety cover is improved as is appropriate.

#### 9.5.9 Summary of the proposed mould scheduling system

The proposed mould scheduling system will schedule separately for each manufacturing group. It schedules for one week at a time; all machines making the same group and colour are scheduled simultaneously. Instructions for running the system are provided as appendix 3.

The production colours are determined to maintain the safety stocks for each colour while using the 'colour freestock' to obtain reasonable batches of each colour..

Each mould is given a priority based on the time until the most urgent product made from it is needed, the current mould status, and any additional costs applicable to that product and mould in their likely location. The additional costs include expediting costs, and the interaction between the moulds in a machine at one time.

The moulds are scheduled in order of priority providing a suitable mould place for that mould remains. The product to be made from the mould is the most urgent product.

##### 9.5.9.1 Intended performance of the system

The system is designed to minimise production costs by using all the

stock in excess of safety stocks, the freestock, in the most appropriate manner.

A lower bound for the production costs is obtained by finding the optimal batch sizes using the 'effective freestock' (see problem A). Section 15.5.8 describes how well the system performs in practice. Section 11.2 provides aggregate estimates of the cost as a function of the freestock.

## 9.6 Testing the algorithm

Various tests were performed to determine how effective the algorithm is. As explained earlier the algorithm is not expected to find the optimum solution, for which extensive searching is required; it is expected to improve current performance. The results show that it does.

Section 9.3.2.1 explains why 'cyclic' solutions are inappropriate here. Since they are commonly used, the best 'cyclic' solutions (that I could find) are presented for comparison. The results clearly indicate that such solutions are inappropriate.

### 9.6.1 Tests - Prepared

I prepared a wide variety of tests. These determine the sensitivity of the algorithm to its control parameters, and show how effective the algorithm is. The results from three typical tests are presented here. The tests are presented in appendix 2.

### 9.6.2 The first test

The first test is typical of problem B. There is one brand with 14 sizes; the object is to minimise the mould changing cost over 13 weeks while meeting a given demand.



Solutions to this problem were produced by me on a 'common-sense' basis, knowing the problem but not using an algorithm, by the existing schedulers, and by an intelligent layman. I then calculated solutions using the algorithm, the best cyclic solution I could find, and the optimal method described in 9.4.

Detailed results are given in table 7. In brief, the optimal method found the optimal solution; the algorithm, with much less effort, gave the next best solution. This is far superior to other solutions except my 'common-sense' solution.

#### 9.6.3 The second test

The second test was similar using the same 14 sizes of one brand. It involves 20 weeks of a continuing run. The optimum solution which provides for the continuing run cannot be found.

The estimated optimal solution has 21.9 mould changes; the optimal procedure gives a solution with 21 mould changes which is not suitable for a continuing run. The scheduling algorithm produces a suitable solution with 22 mould changes.

#### 9.6.4 Realistic tests

Several comparisons were made between the priority algorithm and schedules prepared by existing methods. Table 8 gives the results for one such typical test. (In all cases the priority algorithm was significantly better than existing methods.)

In this example some stockouts were unavoidable but the existing method had many avoidable stockouts. The priority algorithm saved most of these with a couple more mould changes, and with a wider spread of sizes.

Table 7      Comparison of various scheduling methods

Object: To minimise the number of mould changes

	Test 1 13 week terminating run.	Test 2 20 week continuing run
<u>Method</u>		
Estimated optimum	19.1	21.9
Optimum found by optimal procedure	20	21*
Priority algorithm	22	22
My 'common-sense' schedule	23	24
Best original scheduler	26	-
Cyclic solution	27	26
Intelligent layman	37	-

\* Not on the basis of a continuing run (see text).

Table 8 Comparison of scheduling methods - realistic example

	Mould changes	Stockouts (size-weeks)	Spread of sizes Mean	Max	Implied Cost	Deviation from Optimum
Value	10	10	-	2		
Estimated optimum	42	7	8	16	522	-
Priority algorithm	44	11	8.6	11	572	16
Existing method	42	40	6.5	9	838	100
Cyclic solution	52	48	6.5	9	1018	157

The table gives realistic values for the various costs from which it can be seen that the excess costs of the priority algorithm are only 16% of the excess costs for the existing method.

The corresponding cyclic solution is provided for illustration. It is demonstrably inferior to the existing method.

#### 9.6.5 Conclusions

The priority algorithm is superior to existing scheduling techniques, and performs nearly optimally for continuing schedules which form the major problem. It is also more adaptable to the particular circumstances of a problem. It was therefore accepted by the Dunlop management.

## 10.1 Introduction

The product scheduling is divided into two connected modules. The first, mould scheduling, was discussed in chapter 9. This chapter describes the safety stock solution which is developed on the assumption that the mould scheduling solution is adopted.

Section 10.2 reviews the literature on safety stocks. The next two sections develop a model of the effects of safety stocks on shortage costs. Section 10.3 covers the calculation of stockout costs under certain assumption about customer behaviour. Section 10.4 discusses the qualitative effects of various factors on the sales cover as the demand rate is varied. Two possible safety stock policies are proposed in section 10.5.

One of these policies is administratively very convenient, so it was implemented on the introduction of the mould scheduling system. Section 10.6 describes the large resulting reductions in shortage costs. It also shows that this policy is nearly optimal, but that, for products made on one type of machine, the alternative policy could be better. Further study is advised before changing the policy.

## 10.2 Safety stocks - a literature review

Normally, with uncertain demand, a basic model is produced and solved assuming that the demand is known. The stocks needed to provide against this uncertainty, called safety stocks, are calculated separately. A new batch should start when planned stocks fall to their safety level.

The 'scheduling requirements' are defined as the expected cumulative demand plus safety stocks. The objective 'to meet scheduling requirements'.

is thus equivalent to maintaining planned safety stocks.

#### 10.2.1 Simple objectives

The ideal safety stocks depend on the objective. Frequently the true effects of a stockout are unknown. A commonly used objective specifies the maximum allowable frequency of stockouts.

Assuming sales over the lead time are normally distributed with standard deviation  $s$ , one can look up the safety factor  $k$  for any desired level of service. The safety stock should then be  $ks$  (35).

If the same safety factor is used for each product, products made more frequently will have more stockouts per year. One can set the service levels to give the same number of stockouts per year for each product (36); this increases the safety stocks for frequently made products.

#### 10.2.2 A general problem

If the costs depend only on the minimum stock level (and not, for example, on the length of stockout), a general problem is: always in to minimise, or keep acceptably low, the expected 'cost' per occasion

$= \int_x g(y)n(x)dx$  where  $x$  = demand in excess of mean (at minimum stock time)

$s$  = safety stock

$y$  = shortfall ( $=x-s$ ) or, if negative, the stockout

$n(x)$  = distribution of demand

$g(y)$  = cost of a shortfall of  $y$ .

Many common objectives can be expressed in this form. For example, setting  $g$  as zero if  $y$  is negative, and one if  $y$  is positive, gives the first example; setting  $g$  to the 'orders per year', if  $y$  is positive, gives the second example.

More generally  $g$  includes a stockout cost if  $y$  is positive, and a storage cost with  $y$  negative. The safety stock is set to minimise the total cost. If the stockout cost per unit is  $p$  and the storage cost is  $c$ , then the safety stock should be set so that the probability of a shortfall is  $c/(p+c)$  (37).

#### 10.2.3 Use of Lagrangian multipliers

If the total safety stock is specified, and the object is to minimise the total cost over several products, then the storage cost  $c$  can be varied artificially as a Lagrangian multiplier (38). The value  $c^*$  which exactly uses up the available stock is the marginal value of additional inventory.

#### 10.2.4 Alternative stockout assumptions

The true stockout cost is likely to depend on the duration of the stockout. Assuming a uniform sales rate this can be predicted from the maximum shortfall. This permits a wide variety of cost functions,  $g$

A necessary assumption in many cases is that a product is always in stock on completion of a batch.

#### 10.2.5 Interaction between safety stocks and optimal batch sizes

The safety stocks and batch sizes interact. A larger batch means that there is a longer interval between potential stockouts, and so the safety stock required to give the same cover is lower (Note section 9.5.8.2).

This interaction can be allowed for by increasing the set-up cost appropriately (33), if necessary by recursively calculating the optimal values; one iteration will generally suffice. Winters (34)

found that, if the total inventory was constrained well below its optimal value, the safety stocks should bear most of the shortfall.

#### 10.2.6 Applications to this problem

In this problem, the total stocks are specified by the machine loading module, and the split between safety stocks and freestock is determined so that the marginal value of additional inventory of either kind is equal. Lagrangian multipliers may be appropriate in allocating safety stocks.

#### 10.3 Estimation of the stockout costs

An unusual feature of this problem is that customers will generally accept only deliveries which include the full size range ordered. The dissatisfaction with a partial delivery can make it as bad to be short of one size as of many. To estimate the stockout cost function one must make certain assumptions about customers' behaviour.

##### 10.3.1 Assumptions about customers' behaviour during a shortage

To permit a reasonable representation of the problem some assumptions are made about customers' behaviour. The assumptions are fairly realistic, but not exact.

There is little switching to other brands during a shortage, thus the effects of shortfalls of different brands are assumed to be independent. The following assumptions apply to the sizes within one brand.

1. Each customer has a range of sizes essential to his order. The sizes can be ordered so that 'i is less essential than j' means that if i is essential, then so is j.



2. A stockout cost is incurred for all customers who are short of an essential size. This cost depends on the shortfall and not on the number of essential sizes which are short.
3. Priority customers have larger ranges of essential sizes.
4. Priority customers are served first. Stock is reserved for such customers until their orders can be completed.
5. The stockout cost is proportional to the duration of the shortfall, and is an increasing function of the shortfall since larger stockouts affect higher priority customers.
6. For convenience delayed orders are assumed to have the standard sizeroll. In practice the actual delayed orders are known.

#### 10.3.2 Calculation of the stockout cost

Under these assumptions, an algorithm will calculate the expected stockout cost associated with any set of net stocks.

Briefly, it allocates stocks to priority customers in turn until one size,  $j^*$ , runs out. It is called a 'critical size'. All subsequent customers for whom  $j^*$  is essential are dissatisfied. Stock is reserved for priority customers needing  $j^*$ . Any left is allocated to other customers until another, more essential, size  $k^*$  runs out. Continuing in this manner until no further demand can be satisfied gives an optimal allocation for these assumptions.

The stockout cost for any size is its contribution to the total stockout cost. It depends on the number and priority of customers for whom this was the 'critical size'.

#### 10.4 Derivation of the safety stock policy

##### 10.4.1 The problem

The problem is to find an appropriate policy for setting the safety stocks by size and brand to minimise the expected stockout costs given the batch quantities for each product.

##### 10.4.2 Division of the safety stock between brands

Since shortfalls of different brands are independent one can determine safety stocks within one brand independently of other brands. In dividing safety stock between brands within a manufacturing group, the company's policy is to give customers of equal priority an equal service (see 3.6).

Most brands have a similar range of customers. The standard deviation of monthly sales is roughly proportional to the sales. It is slightly larger for low sales brands, but this is balanced by lower priority for buyers of these brands. A policy of setting the safety stocks in proportion to the demand should give equal service to equal priority customers. (This is still true when the proposed allocation to sizes within brands is considered.)

A few priority customers have their own brands. They receive better service through greater safety stocks. The sales department can best determine individual needs, so they allocate the safety stocks between brands with advice on the likely effects of specific policies.

##### 10.4.3 Summary of the approach employed

The general cost function is an extremely complicated function of the net stocks involving a series of integrals between variable bounds. Fortunately a reasonable upper bound for the cost can be obtained by

assuming all sizes are essential. There is then only one 'critical size', this bears the full stockout cost.

For an optimal policy the marginal value of extra safety stock for each size should be equal. One can deduce from this an appropriate probability for a given size to be the 'critical size'.

By altering the safety stocks one can adjust these probabilities. By examining the distribution of the excess stock above the safety stock, one deduces how the desired probabilities might be achieved. An alternative policy is also produced.

On implementation of the first policy, the desired probabilities were achieved for two machine types but not the third. For these machine types the proposed policy appears optimal; for the third type a move towards the alternative policy might yield an improvement.

Note that only policies for which the safety stock depends on the sizeroll have been considered. There are no obvious workable alternatives.

#### 10.4.4 Estimating the desired probability distribution

##### 10.4.4.1 First estimate

Assuming all sizes are essential (Assumption 7), the 'critical size'  $j^*$  has the lowest sales cover,  $st_j/z_j$ , where  $z_j$  is the sizeroll (see accompanying notation in table 9). The stockout cost is a function only of the balanced stock  $Bal (= st_{j^*}/z_{j^*})$  and not of the critical size (by assumption 2).

Extra safety stock of size  $j^*$  will increase the balanced stock in

Table 9

## Notation used in section 10.4

<u>Symbol</u>	<u>Meaning</u>
$j$	Any size
$st_j$	Actual stock of size $j$
$z_j$	Sizeroll of size $j$
$st_j/z_j$	Sales cover for size $j$
$j^*$	The 'critical' size with lowest sales cover
Bal	The balanced stock, equals the lowest sales cover
$E_j$	The essentiality of size $j$ , i.e. the proportion of customers for whom size $j$ is essential  $E_j = 1$ for moderate and large sizerolls
$Pr(j)$	The probability that $j$ is the 'critical' size.
$w_j$	Variation in stock, actual stock - planned stock
$R_j$	Safety stock of size $j$
$av_j$	Average freestock of size $j$
$H_j$	Ratio of actual to average freestock
$L_j, M_j$	Measures of the variation in demand

inverse proportion to the sizeroll. A marginal change will not alter the critical size. To proceed further an additional assumption is made:-

Assumption 8. The expected marginal stock-out cost is independent of the critical size.

The marginal value of extra safety stock for size  $j$  equals 'the probability that  $j$  is the critical size' times 'the increase in balanced stock' times 'the expected marginal stockout cost'. Since the marginal values should be equal, one deduces that the probability that  $j$  is the critical size,  $Pr(j)$ , should be proportional to its sizeroll  $z_j$ .

#### 10.4.4.2 Corrections for realism

Assumption 7 is inaccurate since sizes with low sizerolls are not essential to all customers. Assumption 8 may be false since such sizes are more likely to cause major stockouts affecting priority customers, but less likely to cause prolonged stockouts since stocks can be rapidly built up.

From subjective opinions at Dunlop Footwear, the latter effects cancel out so assumption 8 can be accepted. Sizes with below half the average sizeroll are not essential to all customers, but the level of essentiality falls off more slowly than the sizeroll, so assumption 7 is rejected.

For convenience, it is assumed that the essentiality,  $E_j$ , of a low usage size is proportional to the square root of its sizeroll. This gives the desired behaviour.

#### 10.4.4.3 Improved estimate of the desired probability distribution

For low usage sizes, additional safety stock only benefits the fraction  $E_j$  of the customers for whom this size is essential. To give a constant marginal value of stock for each size, the probability that any size  $j$  is critical,  $\text{Pr}(j)$ , should be proportional to  $z_j/E_j$ .

Note that while a low usage size is critical, there can also be a large stockout cost associated with a high usage size, but shortages of another low usage size will have negligible effect. This affects the probabilities by less than 1%, given that low usage sizes take about 10% of the demand.

#### 10.4.5 Distribution of the excess stock

A stockout will occur if the variation in stock,  $W_j$ , exceeds the safety stock,  $R_j$ , plus the planned excess stock. Size  $j$  is 'critical' if it has the lowest sales cover  $St_j/z_j$ , hence one considers the distribution of this.

##### 10.4.5.1 The planned excess stock

Since production is by batches, the freestock, or 'planned excess stock', of a size  $j$  will vary between nought and two times its average value,  $Av_j$ . It can be written as  $H_j Av_j$  where  $H_j$  is between 0 and 2.

Now  $Av_j/z_j$  is proportional to  $\sqrt{(p-z_j/z_j)}$  (see 9.3.1.2) where the production rate  $p$  is defined in suitable units so that  $z_j$  equals  $p$  for a size in continuous production. The planned excess stock therefore gives a high cover most of the time for low usage sizes, but negligible cover for high usage sizes.

(see table 10).

If a size has a very high usage, so  $z_j$  exceeds  $p$ , then one mould is always used, with a second on occasions, and the cover  $Av_j/z_j$  is proportional to  $\sqrt{(2p-z_j)/z_j}$  which is medium to low.

#### 10.4.5.2 The variation in stock

Several factors contribute to the variation in stock. The main factors are changes in total sales of the brand, random variations in the sizeroll, bias in estimating the sizeroll, and random and deliberate variations in the production. The relative importance of these factors depends mainly on the sizeroll of the size.

#### 10.4.5.3 Changes in total sales

Changes in total sales will affect the balanced stock but not the critical size unless the sizeroll is very biased. A balanced safety stock provides the best cover here.

#### 10.4.5.4 Random and biased variations in the sizeroll

The sizeroll is the average over orders from all customers. It drifts in time as consumers' preferences alter (and more slowly as the average shoe size of the population increases). This introduces a bias into the estimates of the sizeroll.

To estimate this bias, the sizerolls at different times were compared. The drift is generally lower for low sizerolls than for large sizerolls, but the proportional change is largest for low sizerolls. The hypotheses that the drift is proportional to the sizeroll or to its square root are both tenable, though the latter is more strongly supported by the data.

Table 10 Qualitative effects of various factors on  
the sales cover for different sales rates

Sales rate (as fraction of production rate)

Very low  
Up to 0.08

Low  
0.08 - 0.3

Moderate  
0.3 - 0.9

High  
0.9 - 1+

High

High

Essentiality

Factor

Average freestock

Random variation in sales

Bias in sizeroil

Random variation in production

Deliberate change in production  
(rare)

Overall variance

Type of stockout

Need for safety cover

Enormous

Large

Very large

None

Small

Immense

Large but brief

Rare

Large

Fairly large

Large

Fairly large

Moderate

Large

Large but brief

Occasional

Moderate

Moderate

Moderate

Moderate

Moderate

Moderate

Moderate

Frequent

Tiny

Small

Moderate

Small

Fairly large

Small

Small but prolonged

Very frequent



As well as the bias due to changes in the sizeroll with time, there are the normal random variations in demand. Total orders are the sum of a number of orders from many customers. If their orders are independent, the variance would be proportional to demand (as in a Poisson process). A study of individual orders confirms that this is a valid model. It would explain the greater proportional variation in sizeroll for low usage sizes.

Combining random and biased variations in demand, the variation can best be expressed as  $L_j z_j + M_j \sqrt{z_j}$  where L and M are variables whose distribution is independent of the sizeroll. The change in sales cover due to sales variation is thus  $L_j + M_j / \sqrt{z_j}$  which is large for low usage sizes, but moderate for moderate to large sizerolls.

The standard error of the forecast for the sales in the next two months of one size is about 700 pairs for high sales brands so sales variations can equal one week's production.

#### 10.4.5.5 Random and deliberate variations in production

(see table 10)

Deliberate variations in production are generally due to raw materials shortages or machine breakdowns. They frequently cause major stockouts, but they are known retrospectively and one can act to minimise their effects. Correction will not take long except possibly for high usage sizes without duplicate moulds.

Random variations in production occur because the machines produce at different rates or there are problems with a particular mould. These variations are rarely reported to the planner who learns of them only through the stock position. Routine correction occurs

when a new schedule is prepared and used - a possible delay of two months.

Comparisons of actual and expected production over three month periods revealed a standard deviation of the difference of 200 pairs, so that actual stocks could be 500 pairs below plan.

Random variations will not affect sizes which are made less than one week in eight. They can have a large effect on sizes made, say, one week in four, but as the usage increases random variations become less important since their effect on stock cover decreases.

#### 10.4.5.6 Summary

Combining these effects one can make general statements about the frequency with which the safety stock is needed (see table 10).

For example, for very low usage sizes, safety stock is rarely needed and potential stockouts are large but brief. For high usage moulds, safety stock is frequently required and stockouts are small but prolonged.

#### 10.5 Proposed allocation of safety stocks between sizes

From the qualitative analyses above and in table 10, it appears that the frequency with which safety stock is required increases approximately in proportion to the sizeroll. The ideal frequency with which each size should be critical is roughly of this nature. This suggests that the safety stock should be proportional to the sizeroll, increasing the cover equally for all brands and giving maximum protection against an increase in total sales. This is called policy P.

This is an administratively convenient solution and one which would be

naturally accepted by the company, so I decided to implement it and monitor the results.

#### 10.5.1 Alternative policies

The 'normal' policy would be to set the safety stocks in proportion to the standard deviation of demand, which in this case would be a mixture of linear and square root terms. Moving towards such a policy would decrease stockouts of low usage sizes, and increase them for high usage sizes.

Define policy Q as setting safety stocks in proportion to the square root of the sizeroll. Mixed policies are possible, for example a policy of 70%P and 30%Q allocates 70% of safety stocks in proportion to the sizeroll and 30% in proportion to its square root.

Further policies initially appear plausible, e.g. increasing safety stocks for high and low usage sizes, but decreasing it for intermediate sizes. However these have not been examined since there is no evidence to recommend any other policy (see 10.6.1).

#### 10.5.2 Negative safety stocks

It is possible that demand is so high that the total safety stocks are negative implying some unsatisfied demand. At such times the object is to maximise the potential sales, so the shortfall should be spread evenly between the sizes in proportion to their sizeroll so that all sales are equally delayed. Policy P is therefore appropriate even when safety stocks are negative.

### 10.6 The effectiveness of the safety stock policy

#### 10.6.1 Results on implementation of safety stock policy P

Policy P was incorporated into the pilot version of the new product

scheduling system (see 15.4). To show how effective this policy is, two tests were made after it had been in operation for some time.

In the first test, five dates were selected; two, lettered A and B, were before implementation, and three, C, D and E, were after implementation. Table 11 shows how greatly the effective use of safety stocks increased after implementation. This demonstrates that policy P, when used in conjunction with the new mould scheduling system, is clearly beneficial. (For further details see 15.7).

The second test was to examine the distribution of the critical sizes. Each product was classified according to the mould it uses as low, moderate, or high usage (as in table 10). The critical size for each brand was determined on five separate dates after implementation including C, D and E. Table 12 presents the actual and ideal frequencies with which the critical size comes from each mould class, where the ideal frequencies are proportional to the sales rate divided by the essentiality (see 10.4.4.3).

As can be seen from table 12, the actual and ideal frequencies are very close except for the products made on the canvas machines. The Chi-square is a standard statistical measure for goodness-of-fit. It confirms that the fit is good except for the canvas machines where there is only a 5% chance that such a poor fit could occur by chance if policy P were optimal.

The conclusion from these tests is that policy P is certainly an improvement on the previous performance, and that it appears optimal on the protective machines. It seems likely that an alternative policy would be better on the canvas machines. A move towards policy Q appears ideal for these machines since it would decrease the

Table 11    Improvements in the effective use of planned balanced stock  
upon implementation of safety stock policy P

Percentage of total shortage cost which was avoidable

	Machine type			
	Small Protective	Large Protective	Canvas	Mean
<u>Before policy P was implemented</u>				
A	100	97	100	
B	56	79	89	
Average	69	83	98	83
<u>After policy P was implemented</u>				
C	-51*	4	48	
D	35	20	67	
E	73	3	-67*	
Average	33	17	36	29

\* Negative values indicate better than optimal expected performance due to exceptional circumstances (see 15.7.3.6).

Table 12 Comparison of post implementation and ideal frequencies  
with which the critical size comes from each mould class

Machine type	Frequency	Class of mould			Chi-square (measures goodness-of-fit)
		Low usage	Moderate usage	High usage	
Small Protective	Observed	3	8	13	0.77
	Ideal	2.68	6.30	15.02	
Large Protective	Observed	5	14	26	0.65
	Ideal	5.59	16.10	23.31	
Canvas	Observed	8	12	-	6.06*
	Ideal	3.96	14.55	1.49	
All Machines	Observed	16	34	39	1.41
	Ideal	12.23	36.95	39.82	

\* There is only a 5% probability that such a large difference could occur by chance.

Source. Computer stock records processed as in Appendix 6.  
 Each observation requires approximately 100 calculations.

the frequency with which low usage sizes were critical, and increase it for high usage sizes. No other policy is suggested from these results.

#### 10.6.2 Potential gains from switching towards policy Q

The safety stock policy employed before implementation of the scheduling system was ill-defined but resembled policy P. It is therefore always meaningful to talk of switching towards policy Q. The effects of such a switch were calculated for each of the dates A to E. The primary concern is with dates C to E which are after policy P was implemented; figures before implementation are provided to show how a change in mould scheduling policy can alter the appropriate safety stock policy.

Table 13 shows the potential increases in the essential balanced stocks if policy Q had been partly implemented, while table 14 shows the resulting reductions (or increases) in stockout costs. The 'stock transferred' refers to the sum of the differences between the safety stocks under the two policies. Both tables show the marginal gain from a 10% switch towards policy Q. Further movement towards policy Q would give decreasing marginal gains or increasing losses.

##### 10.6.2.1 Interpretation of the results before policy P was implemented

Before the new scheduling system was introduced it would have been worthwhile to switch towards policy Q on all machines with potential gains of around £2,500 per year from a 10% switch. This result is unsurprising since literature often recommends setting the safety stocks in proportion to the square root of the

Table 13      Increases in the essential balanced stocks with a  
10% switch towards policy Q

	Machine Type			Overall Mean
	Small Protective	Large Protective	Canvas	
Stock transferred (pairs)	2,220	3,740	2,250	2,740
<u>Dates before policy P was implemented</u>				
(for comparative purposes)				
A	338	499	-200	
B	321	305	758	
Mean gain before imple- mentation	330	402	289	340
<u>Dates after policy P was implemented</u>				
(major results)				
C	539	-144	421	
D	75	99	536	
E	-154	-375	645	
Mean gain (loss) after implementation	153	-140	534	182
	GAIN	LOSS	GAIN	

Source. Computer stock and orders records processed as in appendix 6.



Table 14      Reductions in the stockout costs (£ per month)  
with a 10% switch towards policy Q

	Small Protective	Machine Type Large Protective	Canvas	Mean
Stock transferred (pairs)	2,220	3,740	2,250	2,740
<u>Dates before policy P was implemented</u> (for comparative purposes)				
A	31	179	-40	
B	51	107	92	
Mean saving before implementation	41	143	26	70
<u>Dates after policy P was implemented</u> (major results)				
C	-9	19	60	
D	2	34	60	
E	-3	-138	28	
Mean saving (loss) after implementation	-4 LOSS	-28 LOSS	49 GAIN	6

Source. Computer stock and orders records processed as in appendix 6.

demand (e.g. 39).

The mould scheduling policy implemented at the same time as policy P altered the batch sizes, increasing them for low usage moulds, and therefore increasing the sales cover for these moulds (see 10.4.5). It was therefore expected that policy Q, which has a similar effect, would be less appropriate after the implementation of policy P and the scheduling policy. This is borne out in the next section.

(Note: There is one unexpected result - for date A on the canvas machines - when policy Q was not worthwhile. Investigation revealed that many low usage products had been made very shortly before that date giving this exceptional result.)

#### 10.6.2.2 Interpretation of the results after policy P was implemented

There is a clear distinction between the results for the protective and canvas machines. There are consistent gains from switching towards policy Q on the canvas machine. These are shown both in decreased stockout costs (table 14) and increased balanced stocks (table 13).

However, for the protective machines, there are both gains and losses from switching towards policy Q with a slight net loss overall, although the average balanced stocks rise. As expected, this contrasts strongly with the situation before implementation.

There was no 'a priori' reason to expect a difference between the machine types but, on looking back, one likely explanation can be found. The scheduler did not fully agree with the new system so, on the canvas machines, he tended to remove low usage moulds before

the scheduled quantity had been produced. This is possible on the canvas machines since changes occur mid-week so can be brought forward, but not on the protective machines where mould changes only occur at the weekend. This action would reduce the cover for low usage moulds giving the observed effect.

(Note: this was the only systematic alteration made to the computed schedules. Other minor alterations were necessitated by specific problems).

#### 10.6.3 Proposed action

A new scheduler was recently appointed. He abides even more closely to the computed schedules. This should further reduce production and stockout costs (see chapter 15); it should also make a switch towards policy Q less appropriate for the canvas machines.

Since policy P appears optimal for the protective machines and may yet be optimal for the canvas machines, I propose that the safety stock policy should remain unaltered. The critical sizes should continue to be monitored at quarterly intervals and their distribution should be compared with the ideal distribution. If low usage moulds continue to be critical too frequently, the safety stock policy for the canvas machines should move towards policy Q.

## CHAPTER 11 THE MACHINE LOADING SOLUTION

### 11.1 Introduction

The machine loading problem is to determine which manufacturing groups to produce on each machine in each week, and also to decide how much of the production should be balanced stock. This is the aggregate part of production scheduling and precedes the mould loading (see chapter 9).

The true costs depend on the production and stocks of each product - a particular size of a particular brand. The machine loading cannot possibly consider every product, so an aggregate cost model is used. This model, based on the stocks and production of each manufacturing group, is developed in section 11.2. The optimal split of freestock into its component parts is determined in section 11.3.

Section 11.4 reviews the literature on production planning with seasonal stochastic (i.e. variable, not known) demand and set-up costs. This has some overlap with section 9.2. The conclusion of this review is that no generally applicable optimal solution technique exists.

Section 11.5 therefore describes a proposed machine loading system soundly based on the optimal solutions to simpler problems. The full system is explained in Appendix 4 with details of the major practical problems given in section 11.6. Section 11.7 explains how the product scheduling is controlled.

Section 11.8 shows that the proposed system compares favourably with several alternative approaches and gives near optimal results on a test problem. Insufficient data is available to make a definite comparison with current practice, but a qualitative examination shows that there would almost certainly be significant improvements on implementation. Unfortunately this has been delayed until late 1976

as a result of unavoidable delays in full implementation of the product scheduling, as described in chapter 15.

## 11.2 An aggregate cost model

The true costs depend on the production and stocks of each size and brand. Assuming optimal product scheduling, the approximate costs can be estimated from certain aggregate variables. A good model requiring few variables is derived in this section.

### 11.2.1 Assumptions behind the model

The model assumes that the resources such as machines are known and fixed, as are the labour force and hours to be worked each week. These are all pre-determined by the management while resource planning (see chapter 12).

There is no control over the demand since price-levels are set outside the planning system and unsatisfied demand is backlogged. The 'net stock' is the current stock minus unsatisfied demand.

### 11.2.2 Background to the model

The controlled variables are the quantities of each manufacturing group to produce each week. These are subject to a fixed total for the production hours. The expected cost of a machine loading schedule is the sum of the weekly costs for each manufacturing group. Only costs such as set-up costs which vary with the schedule need be considered; labour costs, for example, are independent of the schedule and can be ignored.

The relevant components of the weekly cost for one manufacturing group are the storage cost, the shortage cost and, during production, the production and set-up costs. Expediting costs may also arise for

expediting raw materials.

### 11.2.3 The weekly costs for a manufacturing group

The model is now introduced; it is then explained and justified, certain parameters are then derived.

Using the notation in table 15, the weekly costs are the sum of the storage, shortage, production and expediting costs given below:-

$$\begin{aligned}\text{Storage costs} &= V.I.St \\ \text{Shortage cost} &= P \cdot \int_{Bal}^{\infty} (Bal-d) pr(d) dd \\ &= \text{Penalty cost per unit} \times \text{Expected shortfall} \\ \text{Production cost} &= SU \quad \text{on set-up} \\ &= K/PFr \quad \text{during production} \\ \text{Expediting cost} &= E.q^* \\ \text{where } St &= Bal + PFr + InFr + UFr\end{aligned}$$

### 11.2.4 Interpretation of the model

The storage cost equals the product of the total stock, its average value per unit and the interest rate per week. The shortage cost is proportional to the shortfall with penalty cost, P. The expression being integrated is the expected shortfall.

The production cost is inversely proportional to the effective planned freestock, PFr. K is the constant of proportionality (see 9.3.1.2 for justification of this form of cost). The set-up cost, SU, covers the extra mould changing and additional administrative costs.

The expediting cost, if any raw materials need expediting, is the expected cost per unit multiplied by quantity expedited. The former cost will vary with individual circumstances.

Table 15

## Notation in Aggregate Cost Model

<u>Symbol</u>	<u>Interpretation</u>
St	Total stock (of a manufacturing group)
Bal	Expected balanced stock
PFr	Effective part of planned freestock
InFr	Ineffective freestock
UFr	Unplanned freestock
$q^*$	Quantity expedited
Pr(d)	Probability distribution function of d, the difference between actual and expected demand
V	Value of stock
I	Interest rate per week
P	Penalty cost per unit shortfall per week
K	Production cost constant
SU	Set-up cost
E	Expediting cost

### 11.2.5 Justification of the model

#### 11.2.5.1 Storage costs

The production cost per unit production time varies little within a manufacturing group, moreover the production policy keeps the average stocks of each size closely proportional to the demand. Therefore setting the storage costs proportional to the total stock is very accurate.

#### 11.2.5.2 Shortage costs

The true shortage costs cannot be obtained directly from any records but must be estimated from opinions of the sales staff. Their general opinion is that the cost of a shortfall is proportional to the product of the unsatisfied demand the number of weeks delay, but costs may rise more sharply for long delays. The model assumes that the weekly cost is proportional to the shortfall. It is thus compatible with sales opinions except possibly for long delays.

Estimation of the expected shortfall requires knowledge of the probability distribution of demand. The most important aspect of this is the variability of demand, which is measured by a statistical measure, the standard deviation. The expected shortfall is a function of the balanced stock and the standard deviation, and falls off rapidly as their ratio increases. For any specified probability distribution, this function can easily be calculated.

#### 11.2.5.3 Expediting costs

Since only one raw material would generally need expediting at any time, the expediting cost per unit will be constant giving the



relationship assumed in the model. Note that this cost will vary with time.

#### 11.2.5.4 Production costs

There are no production costs for a manufacturing group while it is not being produced. During production, the costs are greater on set-up than in subsequent weeks because a complete machine change is made on set-up, hence the set-up cost. A set-up also means that many workers must switch to other jobs, and causes administrative inconvenience. These can be costed and included in the set-up cost.

##### 11.2.5.4.1 Class two (low-volume) manufacturing groups

Manufacturing groups are divided into two classes. Class one groups contain high-volume brands and are in production for most of the time; class two groups contain low-volume brands and are produced in short batches (see also 7.6.1).

Each product in a class two group must generally be produced in each batch regardless of the batch size. Therefore the minimum number of mould and colour changes is independent of the batch size; furthermore practical schedules have this minimum cost. To represent this in the model, the full mould and colour changing costs for a batch are included in the set-up cost and there is no additional weekly cost.

##### 11.2.5.4.2 Class one manufacturing groups

Class one manufacturing groups are in production for most of the year, indeed some are in continuous production. One cannot therefore manufacture each product only once per batch since this would cause permanent shortfalls. The production policy is more

complicated for class one groups.

The production costs are the sum of the mould changing, colour changing and size-mix costs. Section 9.5 showed that the freestock could be divided into effective and ineffective free-stock attributed to each of the moulds, colours and size-mix.

The batch quantities are proportional to the effective freestock by mould or by colour, and the production costs (over a long period) are inversely proportional to the batch quantities, so each type of production cost is inversely proportional to its effective freestock. Therefore assuming the freestock is split optimally into its component parts (see 11.3) the production costs are inversely proportional to the planned effective freestock.

#### 11.2.6 Summary

This completes the validation of the model. It shows that a small set of aggregate variables can give a reasonable aggregate cost model. Summarising, the shortage costs decrease as the balanced stock increases; the production costs decrease as the freestock increases, while storage costs increase as the total stock increases.

Optimisation will involve determining the appropriate stock level, and the optimal split of stock into freestock and balanced stock. Before that, the optimal split of the freestock must be found.

#### 11.3 The optimal split of freestock in the model

The freestock is the stock in excess of safety stocks. It is a necessary byproduct of batch production since without freestocks every product would need to be produced every day.

Almost all production is initially freestock; as the stocks fall it

will become a part of the safety stock, and eventually it will be sold. The classification is convenient for examining the model, it has no effect on the physical stocks.

This also applies to the component parts of the freestock. These are the 'ineffective freestock',  $Inf_r$ ; the effective 'mould freestock',  $MFr$ ; the effective 'colour freestock',  $CFr$ ; and the effective 'range freestock',  $RFr$ .

The 'ineffective freestock' is a byproduct of the discrete scheduling period (see 8.5.1), since whenever a mould or colour change is necessary during a week it must occur at the beginning of that week. The remaining stocks of that size or colour are, at that time, ineffective in reducing production costs.

The 'mould freestock' for products made from one mould increases while the mould is in production. The mould need not be used again until its freestock falls to zero. Likewise the 'colour freestock' for products of one colour increases while that colour is in production. The colour need not be run again until its freestock falls to zero.

Finally the 'range freestock' is spread over sizes which are not suitable with the current size-mix in production. It ensures that a mould will not be needed until a machine is again adjusted suitably for production from that mould (see 8.3).

#### 11.3.1 Mould changing costs

##### Notation

- $A_i$  = Average effective freestock of mould  $i$
- $S_i$  = Sales rate for mould  $i$
- $f_i$  = Mould changing frequency for mould  $i$

$p$  = Production rate common to all moulds  
 $MC$  = Mould changing cost  
 $MFr$  = Effective mould freestock  
 $K, SQ$  = Constants

The average weekly mould changing cost is  $\sum MC.f_i$ . Section 9.3 discussed the minimisation of this cost. Later, section 9.5 showed that these optimal batch quantities could not be moulded, but that for cost estimation one can use these values.

$A_i$  should be proportional to  $\sqrt{S_i(p-S_i)}$ ; let  $A_i$  equal  $k\sqrt{S_i(p-S_i)}$  and let  $SQ$  equal  $\sum_i \sqrt{S_i(p-S_i)}$ , then  $k$  equals  $MFr/SQ$ . (Note  $SQ$  is a constant determined by the manufacturing group).

Now  $f_i$  is the sales rate divided by the batch quantity, hence  $f_i$  equals  $(p-S_i)S_i/(2A_i p)$  (from 9.3), so the optimal  $f_i$  is  $\sqrt{S_i(p-S_i)}/2pk$ .

Adding over all moulds gives the minimum weekly mould changing cost as  $MC.SQ/2pk$  or  $MC.SQ^2/2p.MFr$ .

Typically  $SQ$  equals  $4p.Numsize/9$  where  $Numsize$  is the number of distinct moulds, so the aggregate estimate for the weekly mould changing cost is  $MC.Numsize^2.p/10.1 MFr$ .

### 11.3.2 Colour changing costs

#### Notation

$CC$  = Colour changing cost  
 $CFr$  = Effective colour freestock  
 $S_i'$  = Sales rate for colour  $i$   
 $p'$  = Production rate per machine ( $=5p$ )  
 $CQ$  =  $\sum_i \sqrt{S_i'(p'-S_i')}$

The same analysis can be applied to colour changing costs to give the minimum weekly colour changing cost as  $CC.CQ^2/2p'.CFr.$

The sum of the sales rate for the 'Ncolour' colours equals the production rate.  $CQ$  is maximised when all  $S_i$  are equal when  $CQ = p'\sqrt{Ncolour-1}$ ; more typically  $CQ$  is eight ninths of this value. Therefore the aggregate estimate for the weekly colour-changing cost is  $20p.(Ncolour-1).CC/10.1CFr.$

### 11.3.3 Size-mix costs

The following notation is used in estimating the optimal 'range freestock',  $RFr$ :

An 'inadmissable size' is one not suitable for production in this week.

'Frac' is the proportion of sizes which are inadmissable.

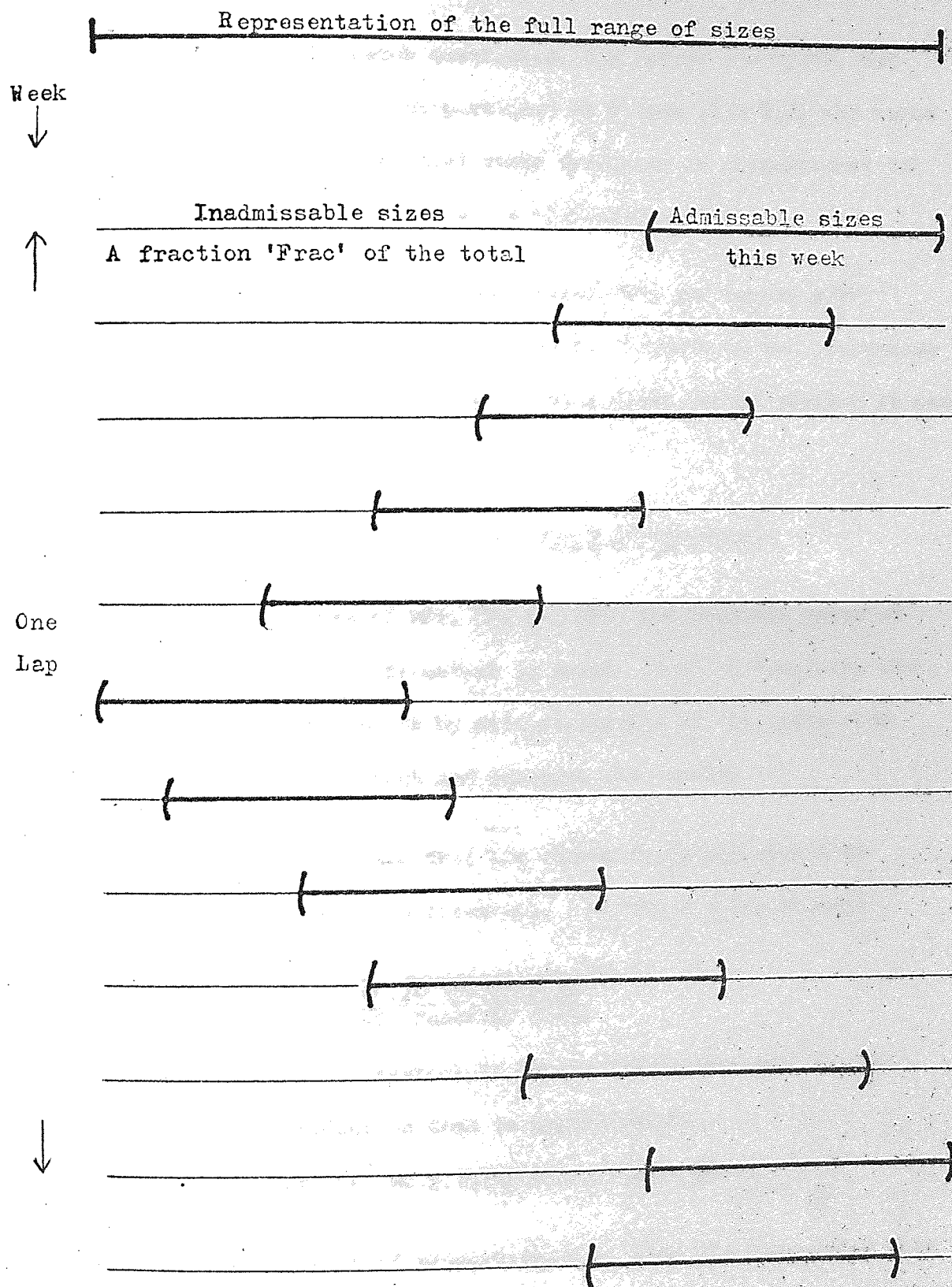
'Lap' is the average time for the ideal size to complete a cycle of all sizes.

The cost of running one size when the machine is ideally suited for another size is given in 8.8.3. This is negligible when the difference is below a critical value, but rises very rapidly above this value. Over all reasonable freestocks, the maximum desired spread of sizes in a machine will approximately equal the difference between the upper and lower critical values (see diagram 18).

At any time sizes which exceed the critical spread are inadmissable for production. These are a fraction 'Frac' of the total. The ideal size for the machine must vary with time so that all sizes are admissible at some time; let 'Lap' be the average time for one cycle (see diagram 23). An inadmissable size must wait until a suitable point in the cycle before it is admissible, this time will be proportional

Diagram 23

THE VARIATION OF ADMISSABLE SIZES WITH TIME



See diagram 10 for example of such a mould schedule



to  $\text{Frac} \times \text{Lap}$ . The range freestock,  $\text{RFr}$ , must be sufficient to cover the demand for all inadmissible sizes until they become admissible, so  $\text{RFr}$  is proportional to  $\text{Lap} \times \text{Frac}^2$ .

Now, the greater the batch quantities, the longer the cycle, but the batch quantities are proportional to  $k$  (see 11.3.2.2) and hence to  $\text{MFr}$ . Therefore the optimal range freestock is proportional to the mould freestock, since  $\text{Frac}$  is virtually constant.

In conclusion, the optimal 'range freestock',  $\text{RFr}$  equals  $A \cdot \text{MFr}$  where  $A$ , the constant of proportionality, depends on the percentage of demand taken by extreme sizes. For a given demand pattern it can be calculated.

#### 11.3.4 Derivation of the optimal split of freestock

At the optimal values of  $\text{MFr}$ ,  $\text{CFr}$  and  $\text{RFr}$ , the marginal value of stock for all types of freestock is equal. One can determine the optimal split of freestock by differentiation of the costs with respect to their freestock and equating the results.

This gives the conclusion that the colour freestock should be proportional to the mould freestock, i.e.  $\text{CFr} = B \cdot \text{MFr}$  where:-

$$B = \sqrt{\frac{\text{CC.20 (Ncolour-1)}}{\text{MC. Numsize}^2 (1+A)}}$$

Therefore the total freestock  $\text{Fr}$  equals  $(1+A+B)\text{MFr} + \text{InFr}$  and the minimum weekly production cost is approximately

$$\text{Numsize}^2 \cdot \text{MC.p.} (1+A) (1+A+B) / 10 (\text{Fr} - \text{InFr}).$$

Let  $K$  be the constant of proportionality, then the production cost is  $K / (\text{Fr} - \text{InFr})$ , i.e.  $K / \text{PFr}$ , where  $\text{PFr}$  is the effective freestock.

#### 11.4 Review of the literature

The problem is to minimise the costs of scheduling the production for groups of products with seasonal stochastic demand revised as the season progresses and with total production hours for each week given. The costs are convex storage and shortage costs, set-up costs and production costs convexly related to net stock. In addition, there are external constraints making some schedules unfeasible.

The important features adding complexity to the problem are underlined. The combination of these makes an exact solution impracticable. Elementary text-books consider most of these separately, but a full solution is available for at most six of the eight features.

Table 16 lists some references indicating which features each reference considers and whether it gives theoretical properties of the solution or an exact or heuristic solution. Diagram 24 shows the inter-relationships between the various approaches. Reference 40 by Veinott examines 'The status of mathematical inventory theory' in detail. Few approaches include seasonal stochastic demand with set-up costs, so approaches with any two of these three features are considered starting with seasonal stochastic demand.

##### 11.4.1 Seasonal stochastic demand

The paper by Hausman and Peterson on 'Multiproduct Production Scheduling for Style Goods with Limited Capacity, Forecast Revisions and Terminal Delivery' (41) comes closest to considering this problem and provides a valuable literature review.

The authors show that the problem can be formulated as a dynamic programming problem but that, for many probability distributions, no



Table 16 Features of the Literature Reviewed

Ref.	Type	Title	Multi-product	Seasonal Demand	Stochastic Demand	Limited Prod'n	Prod'n Costs	Set-Up Costs	Ext. constraints
The Problem									
SEASONAL STOCHASTIC DEMAND									
41	H	Multiproduct seasonal production	x	x	Revised	x	Convex	x	x
16	E	Newspaper-boy problem	x	x	Revised	x	Linear		
42,43	E	Multiproduct newspaper-boy problem	x	x	x	x	Linear		
DETERMINISTIC DEMAND WITH SET-UP COSTS									
44	E	Transportation algorithm		x		x	Linear		
46,47	E	Complex Linear Programming	x	x		x	Segments	x	x
14	E	Holt's Quadratic cost model	x	x	x		Quadratic		
48	T	Horizon Planning (convex)		x			Convex		
49,50	E	Horizon Planning (concave)	x	x			Concave	x	
STOCHASTIC DEMAND WITH SET-UP COSTS									
52	T	Arrow-Harris-Marshak Model			x			x	
55	T	(s,S) solution optimal			x		General	x	
56	T	As above with seasonal demand		x	x		Convex	x	
-	H	Multiproduct (s,S)	x		x	x	Unimodal	x	x
-	H	Multiproduct Economic Batch Quantity	x		x	x	Convex	x	
60,61	T	Optimal single critical number		x	x	x	Linear	x	
62	T	Multiproduct single critical number	x	x	x	x	Convex		

Note Type: E - Exact; H - Heuristic; T - Theoretical.

INTER-RELATIONSHIPS BETWEEN THE  
APPROACHES IN THE LITERATURE



analytical solution is possible even for the one-period single-product problem. They then derive the (open) solution to the final period problem (called the constrained multiproduct newsboy problem) (see 7.2) and extend this to give heuristics for the solution in earlier periods, ignoring the future forecast revisions. Finally, they comment on these heuristics and their failings, but show the value of the forecast revisions through an example.

Their model assumes terminal delivery so all costs are calculated at the end and storage costs are ignored, making the problem much easier. Their approach could be extended in several ways to include the extra features of my problem. There is, however, no immediate way of including set-up costs.

Several other authors have recognised the similarity of the classical newspaper boy problem (16) to the production scheduling problem for seasonal goods. Spurrell (42) provides a method for allocating capacity using a Lagrangian multiplier to adapt the multi-product classical newspaper boy problem. Hodges and Moore (43) extend this when there are several resource constraints. They produce a solution by alternating Linear Programming with solving the newspaper boy problem using the shadow costs from the L.P. Both these papers ignore forecast revisions.

#### 11.4.2 Deterministic demand with set-up costs

To include set-up costs, one must drop either seasonality or stochastic demand. For the deterministic case with linear costs Linear Programming provides an appropriate solution method.

##### 11.4.2.1 Linear Programming

Linear Programming models divide the time interval into a number



of discrete periods. Typically, the major variables  $p_{ij}$  represent the production in period  $i$  of product  $j$ , with constraints that the stock at any time be positive (although this can be replaced by a penalty cost on shortages).

If the only costs are production and storage costs, with constraints on the production in any period but possibly overtime available at higher cost, then the problem can be solved by the Transportation algorithm (44). Each variable represents the production of a product in one period by a certain method for sale in another period.

Several authors have shown that there is a trivial solution to this problem with only one product. This is to make the production as late as possible, except that normal time can be used to avoid overtime if it is fewer than  $K$  periods early where  $K$  is easily calculable (45). If there are several products a similar situation applies but the exact solution is not trivial though the solution obtained manually will be almost optimal and achieved at a lower cost in general.

As we add complexity to the problem, the advantages of using L.P. increase (as does the size of the problem). In particular, convex costs can be represented as a series of linear cost functions with bounds over which each applies. Fixed production hours over several products can be specified by a constraint. The demand, since it is assumed known, can be seasonal and external constraints of a suitable form are readily included, e.g. (46).

Set-ups can be included principally by using Integer Programming which is very costly. An interesting alternative is mentioned by Lasdon and Terjung (47) who have a variable for each possible set-up

pattern (if there are  $n$  periods there are  $2^n - 1$  such patterns with some production). Only active patterns are included in the solution procedure and a separate dynamic programming model finds the next set-up pattern to be applied.

The advantages of the L.P. models are that they give an exact solution, even if at a considerable cost for a reasonable size problem, and that the large amount of knowledge about them can be used for example to give the marginal values of relaxing certain constraints. The disadvantages are the size of the problem, the requirement that demand be known, particularly if the fluctuations can in fact be large, and the non-integral solutions.

#### 11.4.2.2 Holt's quadratic cost model

Holt, Modigliani, Muth and Simon (14) propose a quadratic cost model. The costs include normal and overtime pay; hiring and fixing costs; and storage, shortage and production costs related to the total stock level. Other costs could be included providing they vary quadratically and providing there are no constraints on the allowable values of their variables.

The solution minimising expected cost specifies the production level, overtime and work force as linear functions of the expected demand and the current values of these variables. A great advantage of this model is that it generates the optimal decision for the next period, even if the demand is stochastic, providing the demand estimates are unbiased.

The model is designed for use in aggregate production planning. In these circumstances it should rarely generate infeasible solutions.

However, in the machine loading, one is allocating the aggregate production between major products and the costs are such that each product will not necessarily be made in each time period, thus certain variables have an essentially discrete nature. Furthermore, there are constraints on individual products which might well be violated with a free solution. So the model is not well suited to this specific problem; moreover it cannot easily be adapted.

#### 11.4.2.3 Horizon planning

Horizon planning is appropriate for a single product with multi-period deterministic demand. The object is to minimise production plus storage costs; stockouts are not permitted. The production in any period is unconstrained.

The form of the solution depends on the nature of the production costs. With strictly convex production costs, continuous production is assumed. With concave costs, possibly including a set-up cost, discrete time intervals are assumed and production is completed within the period. Linear storage costs are generally assumed.

The common feature of the solutions is that there exist 'horizons' such that the whole period can be divided into a number of independent sub-intervals. Within each sub-interval, a fundamental solution depending only on the demand to the horizon is optimal.

##### 11.4.2.3.1 Convex costs

A 'fundamental solution' satisfies the condition that the marginal cost of production plus storage until the horizon is constant within the sub-interval (48). If feasible it gives the optimal way of reaching a specified future stock. It is determined

uniquely by the initial production rate.

The optimal scheduling policy is to pick the highest initial production rate for which the inventory is ever again zero. This point is the 'horizon'. Another fundamental solution with a lower production rate is followed from that time.

If storage costs are negligible, a fixed production rate is optimal. Otherwise only qualitative properties of the solution are much used.

#### 11.4.2.3.2 Concave costs

Concave costs generally arise as a set-up cost plus a fixed cost per unit, but the theory applies generally. In an optimal solution, one need only consider fundamental solutions for which either the opening stock or the production is zero. At a 'regeneration point', the quantity produced will equal the demand for an exact number of periods - thus defining the horizon (26).

Since only a small number of possibilities need to be considered in each period, Dynamic Programming finds the optimal solution efficiently. Crabill and Jaquette (49) extend this approach to the problem where only one of several products may use the production facility in any period. Zangwill (50) shows that backlogging can be allowed without altering the nature of the solution.

#### 11.4.2.3.3 Conclusions on horizon planning

With constant demand, the concave cost model gives similar results to the Economic Batch Quantity methods for much more effort. It is efficient for non-stationary costs or demand when a simple

solution cannot be obtained.

The horizon planning solutions are unsuitable for stochastic demand, since the demand for an exact number of periods is unknown. Nevertheless one is hopeful that planning horizons, such that subsequent demand can be ignored, will be found for stochastic problems. Symonds (51) provides a heuristic method using calculated safety stocks and the deterministic solution.

#### 11.4.3 Stationary demand with set-up costs

##### 11.4.3.1 The Arrow-Harris-Marshak inventory model

- $x_t$  = Initial stock level in period  $t$
- $y_t$  = Stock level after ordering
- $w_t$  = Demand in period  $t$
- $z_t$  = Sales in period  $t$
- $C(.)$  = Production cost
- $h(.)$  = Holding cost on stock ) Evaluated at the end of  
 ) the period (only one is
- $p(.)$  = Penalty cost for shortages) positive)
- $K$  = Set-up cost
- $r$  = Unit revenue
- $\phi(W_t)$  = Known probability density function of demand
- $a$  = Discount rate

Then costs in period,  $L(y:x) = c(y-x) + \int_0^y (h(y-w) - rw)\phi(w)dw$   
 $+ \int_y^\infty (p(w-y) - rz)\phi(w)dw$

Define  $f_n(x)$  = minimum discounted expected loss if  $x$  is the initial stock, there are  $n$  periods left and an optimal ordering rule is used in this period.

Then  $f_n(x)$  satisfies the functional equation

$$f_n(x) = \min_{y \geq x} (L(y:x) + a \int_0^\infty f(y-z)\phi(w)dw)$$



If anything is ordered, a set-up cost of  $K$  is incurred, the production cost per unit is  $C$ . Thus  $C(x)=0$   $x=0$

$$=K+Cx \quad x>0$$

$$\text{Define } G_n(y) = Cy + \int_0^y (h(y-w) - rw) \phi(w) dw + \int_y^\infty (p(w-y) - rz) \phi(w) dw \\ + a \int_0^\infty f_{n-1}(y-z) \phi(w) dw$$

Then  $f_n(x)$  satisfies the convenient equation: *Optimal costs*

$$f_n(x) = \min_{y \geq x} \begin{bmatrix} -Cx + G(x) \\ K - Cx + G(y) \end{bmatrix} \quad (\text{minimum of above})$$

#### 11.4.3.2 Standard results from the inventory model

Arrow and Karlin in combination with Scarf or Suppes have edited three books (52, 53 and 54) which bring together the early work on stochastic inventory models and establish many theoretical results on the nature of the optimal solution.

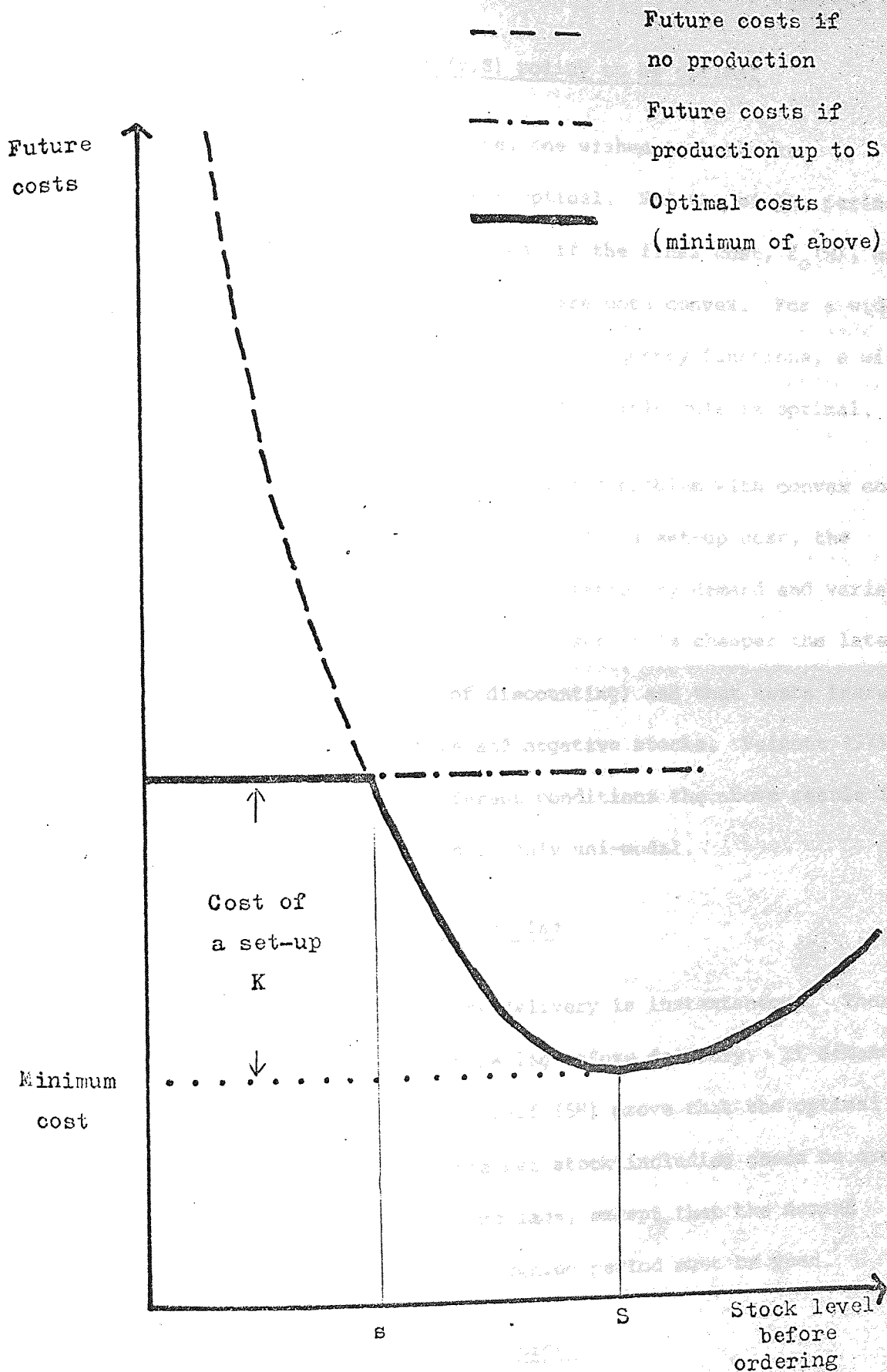
For the one-period problem Karlin (55) shows that the nature of the optimal solution depends on the form of the production cost, and on whether any quantity can be ordered or only certain fixed quantities.

Assuming costs are linear plus a set-up cost  $K$ , and that any quantity can be ordered, the general form of the ordering rule as a function of the current stocks can be involved with several intervals in which no ordering is done and several quantities to order up to. However, if the total cost  $G(y)$  has a unique minimum, then the simple rule - if  $x$  is below  $s$ , order up to  $S$ , otherwise do not order - is optimal (see diagram 25). This is called an  $(s, S)$  policy.

Without set-up costs, but with a minimum order quantity of  $Q$ , the corresponding simple rule is - if  $x$  is below  $s$ , order the minimum multiple of  $Q$  to bring the stock above  $S$ , otherwise do not order -

Diagram 25

COSTS UNDER AN (s,S) PRODUCTION POLICY



Below  $s$  one should produce up to  $S$ .  
 Otherwise there should be no production.

is optimal. With both set-up costs and minimum order quantities there is no correspondingly simple rule.

#### 11.4.3.3 Conditions for an (s,S) policy to be optimal

Since simple rules are easy to use, one wishes to know the circumstances under which they are optimal. For the single period problem, an (s,S) solution is optimal if the final cost,  $f_0(x)$ , and the combined holding and penalty cost are both convex. For a wide range of demand functions, called Polya frequency functions, a wide range of assumptions guarantee that this simple rule is optimal.

Karlin (56) shows that, in the multiperiod problem with convex costs (as above) and linear production costs plus a set-up cost, the optimal policy is (s,S) even with non-stationary demand and variable costs. The only conditions are that a set-up is cheaper the later it is (a natural consequence of discounting) and that costs increase to infinity for large positive and negative stocks. Veinott (57) shows that under slightly different conditions the above result is true even if the cost function is only uni-modal.

#### 11.4.3.4 Effect of delivery time-lag

The preceding discussion assumes delivery is instantaneous. There may however be a significant time lag before delivery. If demand is backlogged, then Karlin and Scarf (58) prove that the optimal policy is a function only of the net stock including goods on order. One can therefore ignore any time lags, except that the demand distribution over the whole intervening period must be used.

#### 11.4.3.5 Limited production resources

Evans (59) discusses the nature of the optimal policy in a multi-

product system with limited production resource. Assuming linear costs and no set-up costs, the total cost is convex and a unique minimum exists. The optimal policy involves moving towards this solution in a general sense, but no precise policy can be stated.

#### 11.4.3.6 Calculating the optimal policy

##### 11.4.3.6.1 Without set-up costs

With a single product and many periods, Karlin (60) shows that there is an 'optimal single critical number,  $s$ ' for each period, such that one should order up to this quantity under linear or convex costs.

If demand is stationary,  $s$  minimises  $(1-a)Cy + L(y;y)$  the cost per period. This can be calculated if  $L$  is differentiable or found graphically.

If demand is seasonal, Karlin (61) shows that the optimal critical numbers can be found as the solution to 23 transcendental equations (with 12 months in a season). His solution is unlikely to be used in practice.

##### 11.4.3.6.2 The multiproduct no set-up cost problem

Veinott (62) gives an 'optimal policy for a multi-product dynamic non-stationary inventory problem'. This is based on the optimal critical numbers for each product increasing from period to period. Unfortunately this property does not hold with demand revisions between periods, since demand is no longer 'more variable' with increasing time.

##### 11.4.3.6.3 With set-up costs

With stationary demand, one can employ renewal theory to determine

the long term probability of occupying any state for a given  $s$  and  $S$  (63). This distribution depends only on  $(S-s)$  and can be explicitly calculated for certain distributions.

The average cost per period is evaluated by applying this distribution to the costs per period. The optimal  $S$  and  $(S-s)$  can be found graphically or possibly analytically.

For non-stationary demand with set-up costs there is no generally applicable solution. Dynamic Programming can be applied to simple problems, but the computation involved makes it impossible in practice. Therefore heuristic solutions, generally based on the exact solutions to simpler problems, must be used.

#### 11.4.4 Forecast revisions

Few production planning papers consider the effect of forecast revisions, possibly because they will only occur after the immediate time horizon so have no effect, but more probably because they introduce major complications.

Hausman and Peterson (41) consider the effect of revisions on their solution by applying a heuristic approach. Murray and Silver (64) produce an exact two-period solution to a simple problem. They show that tables must generally be used to determine the optimal decision.

#### 11.4.5 Summary of the literature review

The literature review shows that only Dynamic Programming will provide an optimal solution to the full problem. It is too general and would be impractical in practice due to the number of calculations required.

Several approaches cover many of the complex features of the problem.

In particular the works by Hausman, Spurrell, Karlin and Veinott appear particularly promising as starting points for a solution.

### 11.5 The proposed approach

The literature review reveals that the optimal solution to the machine loading problem is too complex to be found by a practical algorithm. The proposed approach is therefore heuristic, but it is soundly based on known properties of optimal solutions to related problems.

To maintain an overall view of this solution it is outlined below. The proposal is then derived from the literature. This requires a large number of assumptions, some of these can be proved, the rest can be partially justified. Full details of the practical system are given in Appendix 4, the major points are explained in section 11.6. This system performed well on prepared tests, unfortunately it could not be reliably compared with actual practice (see 11.8) due to lack of data.

#### 11.5.1 Proposal for a machine loading system

The machine loading should be prepared in blocks of one month at a time looking forward to a horizon 6 months to a year ahead. The detailed loading need only be prepared for four to six months, of which the first will probably be fixed by the current schedule.

There are three stages in the preparation of the machine loading for a month. The first stage determines ideal stock levels for each product such that the available production hours are exactly used. A byproduct of this stage is that the implicit marginal value of a production hour is derived.

In the second stage a provisional machine loading is produced. This tries to reach a final stage as close to the ideal stock levels as is possible using near optimal 'trigger stocks' and batch quantities.

This provisional loading may well imply unacceptable peak workloads for certain groups of workers or it may be infeasible for some reason. The costs should not increase much by slight variations of the provisional loading, therefore the machine loading is freely adjusted to produce an acceptable machine loading.

#### 11.5.2 Derivation of this approach

##### 11.5.2.1 Optimal stock levels

Ignoring set-up costs and assuming production is continuous, there is a set of optimal stock levels at which the costs are minimised. Evans (59) shows that these exist and Spurrell (42) shows how to calculate them considering only immediate costs.

Spurrell determines a marginal value of production hours such that the available hours are exactly used producing the various manufacturing groups. This enables the problem to be considered independently for each manufacturing group.

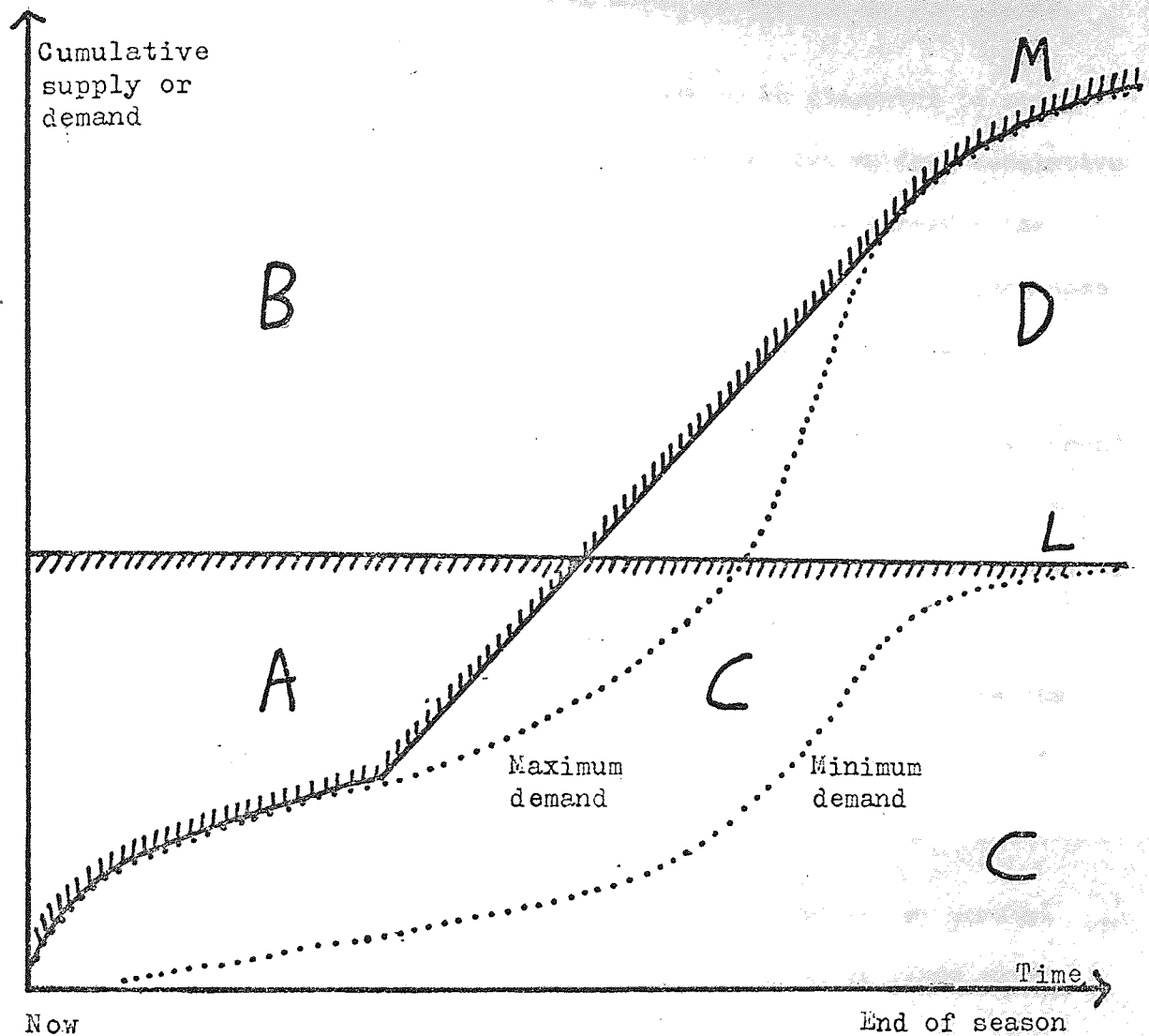
##### 11.5.2.2 'Opportunity costs'

If present stocks exceed their optimal level, then immediate costs will be above their minimum value. Likewise, if the optimal level cannot be reached even with full production, immediate costs will be above their minimum. These extra costs are called 'opportunity costs' and arise because initial stocks were not within an optimal zone (see diagram 26).

Applying the logic of Dynamic Programming to the decisions made in the previous month, the optimal decision then minimises present and future costs. The excess future costs are the 'opportunity costs'

Diagram 26

HOW OPPORTUNITY COSTS VARY WITH THE  
PROJECTED SUPPLY AND TIME OF SEASON



Explanation

Opportunity costs depend upon a comparison of the projected supplies with the ability to meet the demand, whether at its minimum or maximum level, as shown by the dotted lines.

Above line L one may be overstocked - if demand is low. Below curve M one may be understocked - if demand is high. The straight line portion of line M is based on the maximum production rate. The costs rise the further one is on the wrong side of these lines.

In region A there is no risk and no cost. The optimal 'safe' zone.

In region B one may be overstocked; low production is desirable.

In region C one may be understocked; peak production is desirable.

In region D there is general risk; the production policy must balance the risks.



described above; therefore, if these can be estimated with reasonable accuracy, the optimal stock levels can be calculated.

The production hours in each month have to be allocated to some manufacturing group; therefore, in general, the optimal cumulative production of each group increases with time. As a result the optimal stocks for one month are generally within the optimal zone for the following month and there are no opportunity costs.

Opportunity costs will only arise if the estimates of future demand are sharply revised between consecutive months. A sharp fall may reduce the optimal cumulative production to below its desired level, while a sharp rise may make the required production exceed the production capacity for the manufacturing group. Therefore the opportunity costs depend principally upon the probabilities of extreme events.

Except for Dynamic Programming which is too costly, no general procedure is available for calculating opportunity costs so an approximate method is used.

#### 11.5.2.3 The optimal policy with set-up costs

Without set-up costs, the optimal policy is to produce up to the optimal stock level for each manufacturing group or, if this is impossible, as 'near' to it as is feasible.

Set-up costs make frequent production 'starts' undesirable, therefore the stocks should fluctuate around their optimal levels. The minimum level, at which production should be started, is called the 'trigger stock', and the quantity produced is the batch quantity.

Karlin (56) shows that under the conditions of this problem, the optimal production policy is of this nature, i.e. there are not two or more trigger stocks as there might be.

Unfortunately the reintroduction of set-up costs and discrete production has two side-effects. Firstly the problem is no longer separable into sub-problems for each manufacturing group since over-production of one group means that another group must fall behind. Since marginal values of stock are similar around the optimal stock level, intelligent adjustments should increase the costs little.

Secondly, the optimal stock levels can only be reached from certain initial stocks. These will depend on the demand in the preceding month, therefore there are opportunity costs associated with all stock levels.

I assume, since there are no strong grounds for disbelief, that the change is uniform over all points inside the 'optimal zone' and increases similarly outside. I therefore ignore the effects of set-up costs in calculating the opportunity costs. The error in this assumption is probably less than the calculation error even with reliable forecasts.

This leaves the trigger stocks and batch quantities to be determined. Their optimal values vary little if the ratio of the set-up cost to implicit storage cost is doubled. Since production is in weekly units, the figures must be rounded, therefore stationary demand is assumed, as in reference 63, although the true situation is dynamic.

#### 11.5.2.4 The machine loading

The optimal stock level, batch quantity and trigger stock can now be

determined for each manufacturing group. The provisional machine loading keeps as close to these as is practical.

Costs for class two manufacturing groups increase rapidly as one moves away from the optimal level, so these are planned first. Class one groups fit around them as appropriate.

The final adjustments to give an acceptable machine loading should increase costs little since the marginal values of stock for each manufacturing group are similar providing one keeps near the optimal stock levels.

#### 11.6 Practical aspects of the machine loading system

This section describes how the major practical problems of machine loading were solved. Details of the system are supplied in Appendix 4, a manual on machine loading.

##### 11.6.1 Stages in the machine loading

In the first stage of machine loading, data is collected for each manufacturing group. It is processed so that standard cost curves can be used for each manufacturing group. The data collection requires a lot of effort on the first occasion, but little thereafter.

The expected stocks for each future month are projected. Each month is classified according to the stock position so that an appropriate algorithm can be used.

The optimal stocks for each manufacturing group are calculated recursively by estimating the marginal value of a production hour and determining the corresponding stocks from an appropriate graph. The production required is compared with that available and the estimated marginal value is revised.

The trigger stock and batch quantity are determined from a separate graph using the ratio of the set-up cost to the marginal value of stock (which equals the marginal value of a production-hour when measured in appropriate units).

Each class two (low demand) manufacturing group is examined to see whether it should be produced and, if so, how much. A provisional machine loading is then constructed around this. Finally this is adjusted to give an acceptable machine loading.

#### 11.6.2 Initial Data Processing

Little need be said about data collection except that many of the variables are not directly observable. They must be estimated from company costs and policy, the manual gives specific advice on this.

A particular requirement is that the forecast accuracy must be known since the probability of a stockout depends on the ratio of stock to forecast accuracy. The standard models use the 'standard error' of the forecast as a unit of stock. (The probability that twice the standard error is exceeded is approximately one in twenty.)

For simplicity, the shortage costs can be represented by a simple but reliable model which makes it easier to use the standard models. Exact costs can be used if more effort is put into the initial processing.

#### 11.6.3 The optimal split of stock into freestock and balanced stock

One wishes to determine the optimal split of any available stock into its component parts. These are balanced stock, effective freestock, ineffective and unplanned freestock. The latter two types of stock have no beneficial effect on costs and are therefore minimised.

Once the minimum allowances for ineffective and unplanned freestock have been taken out of the stock, the residue must be divided optimally between effective freestock and balanced stock. There is a minimum level for the effective freestock - a consequence of the minimum batch size of one week's production. All extra stock should become balanced stock until the marginal value of balanced stock falls to the marginal value of freestock at its minimum.

Thereafter further stock should be divided between balanced stock and freestock to keep the marginal values of these types of stock equal since the cost is convex in these two variables.

#### 11.6.4 Timing

The machine loading specifies the manufacturing group to be produced on each machine in each week for the next four to six months. It is revised every four to six weeks. The first month of each loading is almost always retained from the previous loading since the raw materials are already being processed.

The machine loading therefore controls the production 5 to 10 weeks ahead. Materials with a long lead time are ordered from the later weeks of this schedule to arrive a few weeks early. It may therefore be difficult to bring forward production of an 'awkward' product by more than a few weeks.

The machine loading is constructed in stages of one month at a time. The month currently being planned is called the 'current' month.

The horizon is such that current decisions have a negligible effect beyond the horizon. It is set as the later of the end of the present season and nine months ahead.

#### 11.6.5 Classification of the supply position

The stocks at the end of each month are projected and the expected ineffective and unplanned freestocks are subtracted. The supply position for each month is classified mainly by the ratio of the residual stock to the standard error of the demand forecast.

If the net residual stock is below one standard error below zero, that month is projected as 'severely understocked'. If the residual is within one standard error of zero, that month is 'slightly understocked'. Otherwise the position is generally 'satisfactory'.

However if the total supplies will not be used in the following month, but in a later month classified as 'understocked', then opportunity costs are likely to be incurred in the month which is therefore classified as 'pre-season'. (See diagram 26 earlier).

If current supplies are so large that they will not be exhausted by the end of the season or the time horizon whichever is later, the position is classified as 'overstocked'. Surplus production is put into low cost products for which there is a secure demand pattern.

#### 11.6.6 Determination of optimal stocks

An estimate is made for the marginal value of stock. The standard cost curves appropriate to the supply classification are used to determine the corresponding optimal stocks for each manufacturing group. The implied production is compared with the desired production. The marginal value is raised if the implied production is too high and vice-versa. The calculations are repeated until the desired production level is achieved by a set of optimal stocks.

#### 11.6.7 Calculation of trigger stocks and batch quantities

The trigger stocks and batch quantities are calculated graphically from standard cost curves assuming that the situation remains stationary with the marginal value of stock constant at the level calculated above (see appendix 4).

For these standard curves, the optimal trigger stock decreases very little as the ratio of set-up cost to storage cost increases, while the optimal batch quantity varies approximately with the  $0.4^{\text{th}}$  power of this ratio over typical ranges.

Since demand is not stationary, these estimates are not optimal. The trigger stocks have an immediate effect so these values should be nearly optimal and are accepted. The batch quantities may however be altered; in any case they must be rounded to a whole number of weeks' production. Generally one rounds down if the marginal value of stock will rise in the near future and vice-versa; this caters for all but very sharp changes.

In a 'pre-season' month, this may lead to overproduction of a product; the associated opportunity costs for the peak stock may occasionally make it desirable to further reduce the batch quantity.

#### 11.6.8 Opportunity costs

The true opportunity cost associated with any stock level is the expected excess cost of future decisions starting with that stock instead of the optimal stock. Since one tries to keep near the optimal stocks, opportunity costs are only likely to arise as a result of substantial forecast revisions.

For example, if the forecast demand for a manufacturing group is halved, the current supply will probably exceed the optimal stocks for the end of the month. The opportunity cost incurred is the implied marginal storage cost of this stock minus its value in reducing costs.

Since the forecasting system is not very sophisticated, the opportunity costs cannot be accurately calculated and the following approximation is used.

#### 11.6.8.1 Calculation of opportunity costs

Produce minimum and maximum demand projections for each manufacturing group. One may be overstocked if 'current' stocks (i.e. projected stocks for the specified month) exceed the minimum projected demand during the season; conversely one may be understocked if the maximum projected demand cannot be met even with production at the maximum rate (see diagram 26).

The estimated marginal overstocking cost is assumed to vary uniformly from zero if 'current' stocks equal the minimum projected demand up to a quarter of the marginal value of stock during the season if the 'current' stocks equal the mean projected demand. The marginal understocking cost is estimated similarly; the marginal opportunity cost is the difference between these.

#### 11.6.8.2 Rationale behind the estimates of opportunity costs

The rationale behind these estimates is that if current stocks equal the minimum expected demand, the opportunity costs are negligible. If current stocks equal the mean expected demand, then half the time they will be excessive. By examining realistic situations a



reasonable value for the marginal value of this excessive stock is half the cut-off marginal value of stock, so the average marginal overstocking cost at the mean expected demand is a quarter of the cut-off marginal value of stock.

For convenience the opportunity cost is assumed to be a linear function of the excess of current stocks above the minimum demand. The true relationship depends on the distribution of demand but is probably a higher order function. However while all estimates are crude, as they will be initially, this estimate will suffice and is easy to handle. Once in use, the expected opportunity costs can be compared with the actual values and, if necessary, this rule can be revised.

#### 11.6.9 Creating the machine loading

For each class two manufacturing group (for which the set-up costs are large) production is required if the stock will fall below the trigger stock. If so the batch quantity should be produced starting as close as possible to the time when the stock equals the trigger stock.

The class one groups are fitted around the outline loading produced above. This is done so as to make the final stocks as close to the optimum level as can be achieved.

Finally, slight adjustments may be made to the machine loading to remove undesirable overloads for any group of workers. For example, if two machine changes are scheduled for one weekend, then one can be moved forward or backwards one week.

#### 11.7 Control of the product scheduling

The machine loading is prepared manually. The product schedule is prepared by the computer. The input to this computer program specifies the machine loading, and the desired split of stock into balanced stock and freestock.

For practical reasons, the weekly demand for each product must remain in the same proportion throughout the schedule. Within a brand this is no problem since the sizeroll is constant over a schedule. Between brands, the weekly demands may vary from month to month.

The weekly demand is initially set to the average value over the machine loading period. The stocks at the end of each month for each brand are projected assuming the mould loading performs normally. If these stocks are within 10% of the desired safety stock, these values are accepted. Otherwise the initial demand and weekly demand are adjusted to reduce the difference. This almost always gives an acceptable set of safety stocks. If not, the scheduling period is divided into two parts at the time where the trouble occurs. (See diagram 27 which shows how an unusual demand pattern would be met.)

Note that if all brands have the same seasonal sales pattern, there is no problem since the total demand is allowed to vary each week. It is only differing seasonalities which cause problems.

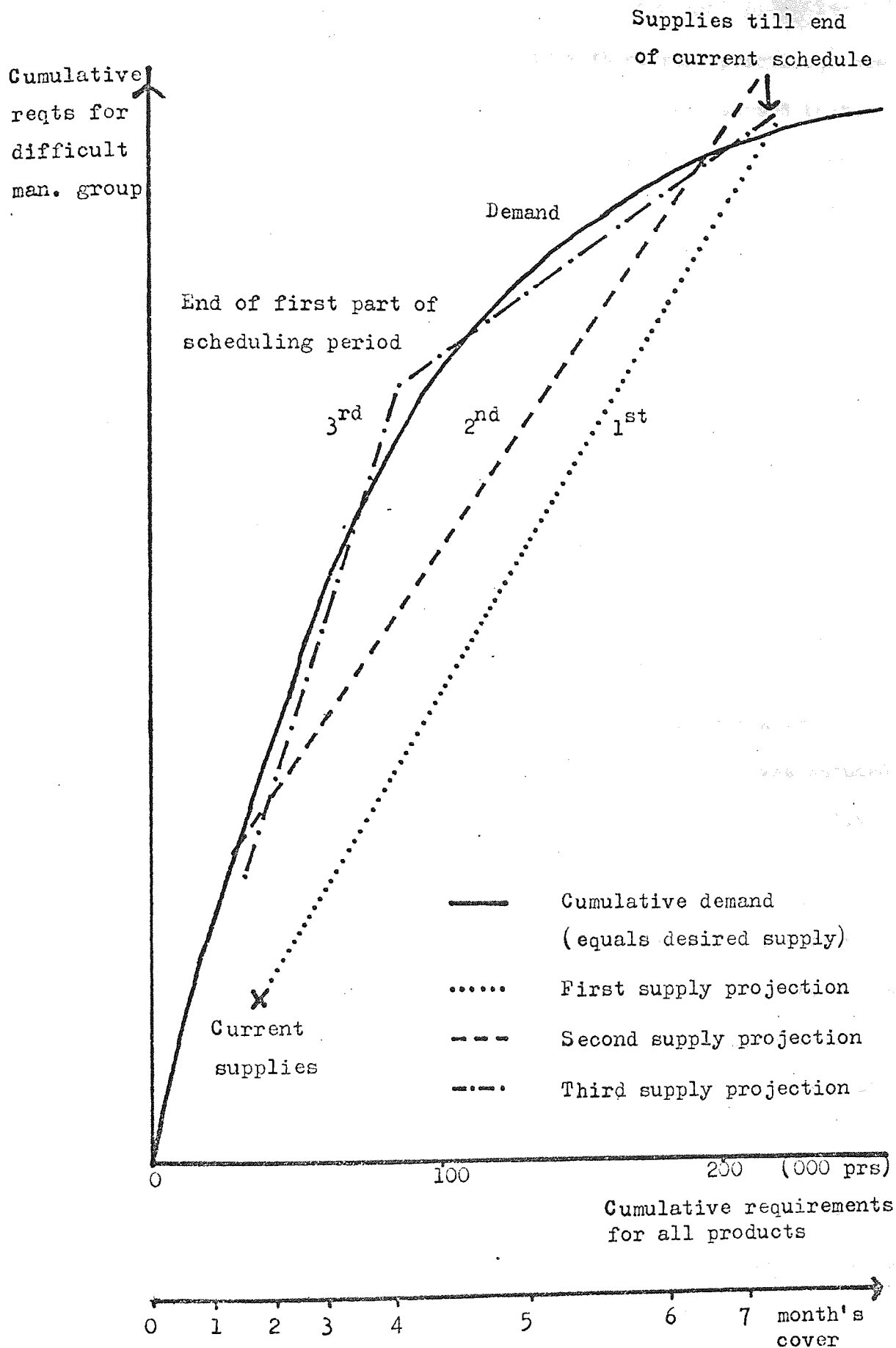
This control routine is included in a computer program which prepares the data for the product scheduling program. These programs are supplied as appendices 7 and 8.

#### 11.8 Testing the machine loading system

The proposed machine loading system has been tested in two ways.

Diagram 27

HOW AN UNUSUAL DEMAND PATTERN IS MET  
BY SUB-DIVIDING THE SCHEDULING PERIOD



Firstly on a prepared test problem where it compared favourably with several alternative techniques.

Secondly it has been qualitatively compared with current practice since there was insufficient data for a full comparison. This showed that, with the recent low-levels of stock, the current performance has been good but with more typical stock levels significant improvements are possible.

#### 11.8.1 The test problem

The test problem involved six manufacturing groups over a nine month period which included two forecast revisions. The costs and seasonality varied between manufacturing groups but there was an overall demand peak in the eighth month, and the final month was the end of the season. Shortages are avoidable except in these final months.

The demand for each group and month was assumed to be normally distributed and independent of other months. The planner was assumed to know the true parameters for each product, although he naturally would not know the actual demand in advance.

Three simulation situations were considered. No forecast revisions were made in the first case; random revisions were made in the second case; in the third case high (but attainable) demand levels were forced. In all cases the actual demand was found as a random variable from the assumed distribution.

The third situation was included because high opportunity costs are likely if demand is unexpectedly high. Any implemented system should cope satisfactorily with this potentially costly situation.

#### 11.8.1.1 The production strategies

A production strategy can generally be classified by a selection rule which determines the product to make next, and a stopping rule which states when to stop production. Detailed results were produced for seven production strategies including the proposed system and a variant of it which ignores opportunity costs.

After testing several strategies, such as producing the Economic Batch Quantities of each group, the overwhelming importance of the decisions in the final two months became apparent. Since full information is available when these decisions are made, it is reasonable to assume nearly optimal decisions will be taken then whatever the production strategy. Strategies including optimal decisions in the final two months are marked with an asterisk in table 17. For these strategies, the production order of the products has been altered if there is an obvious improvement.

The basic selection rule is to make the most urgent product. In two cases the cheapest product is made if none are urgent. In the proposed system, each product has a trigger stock; with low total stocks this selects the most urgent product, with high stocks the set-up and storage costs have a significant effect on the trigger stock.

The basic production rule is to produce until the total requirements are met or another product falls to its safety stock, variously set as two or three standard deviations of the demand. In two cases, if the cheapest product is not in production, production stops when the stock provides 3 or 4 months sales cover.

In one case shortage costs are minimised; the production plan is derived by starting from the desired final stocks and proceeding backwards in time. In another case, the 'Economic Batch Quantity' is produced regardless of other stocks.

These policies are intended to represent the types of policy one is likely to employ in practice. In general they concentrate on minimising one part of the total cost.

#### 11.8.1.2 Results

The results, in increasing cost order, are given in table 17.

The costs are split into production, storage and shortage costs.

The lower bound is the sum of the minimum values of each component cost for reasonable strategies, therefore it is unlikely to be feasible.

The results for the random revisions do not differ significantly from the basic results, so are not given. A few strategies were not tested on the high demand version.

The proposed system achieves near minimum costs for the basic problem. The next best strategy - to minimise shortage costs - is around 6% worse. Other strategies have similar total costs, but vary in their composition of these costs, suggesting that there is a reasonable choice of near optimal solutions. Finally production of the Economic Batch Quantities regardless of actual stocks doubles the total cost.

With the unexpectedly high demand, it is unsurprising that there is a wider gap between the lower bound and the best solution - again achieved by the proposed system. The second best solution is still

Table 17 Comparison of alternative production strategies on the test problem

Strategy	Demand Pattern	Storage Cost	Production Cost	Shortage Cost	Total Cost
Lower bound	Normal	2920	950	230	4100
	High	2900	1000	1000	4900
Proposed system	Normal	2992	950	286	4228
	High	2957	1075	1241	5273
Minimum shortage costs	Normal	3319	950	244	4513
	High	3329	1050	1200	5579
Produce cheapest if none urgent	Normal	3075	1100	395	4570
Give 4 months cover	High	3064	1100	1780	5944
at 0.1% safety stock *					
Proposed system	Normal	3073	1175	408	4656
- no opportunity costs	High	3057	1075	1742	5876
Produce most urgent until another urgent or full quantity produced *	Normal	3316	1000	375	4691
Produce cheapest if none urgent	Normal	2931	1525	409	4865
Give 3 months cover					
at 2.5% safety stock *					
Produce most urgent	Normal	3257	1200	4225	8682
Make the Economic Batch Quantity					

\* Indicates that the optimal decisions were made in the final two months regardless of the production strategy. This typically reduces costs by 500.

to minimise shortage costs; other solutions fall yet further behind, principally because they involve high opportunity costs. In particular, note how poorly the proposed system performs if opportunity costs are ignored.

#### 11.8.1.3 Conclusions

Since most strategies include optimal decisions in the final two months when all the shortages occur, the high shortage costs of some strategies show how poor decisions early on can increase the costs.

The proposed system is clearly superior to other proposed strategies, although a good simple strategy is to minimise shortage costs. I therefore recommend adoption of the proposed system.

#### 11.8.2 Comparison with actual performance

##### 11.8.2.1 Recent years

Recent years have been exceptional in that demand for the company's products has been continually high. As a result there has been a continued backlog of demand and the marginal value of stock has been high. Furthermore forecasts are not needed since the orders have already been received.

The appropriate optimal batch quantities for the class two manufacturing groups are the minimum batch quantities; the freestocks should also be at their minimum values. Since the demand backlog arose, the policies applied in practice have been nearly optimal, particularly since my advice has been accepted.

Minor differences between the proposed systems and actual machine loading have arisen as a result of unstated sales policies. If the



sales policy were to be fully documented, such policies could be incorporated in the proposed system.

#### 11.8.2.2 Earlier years

A few years ago the supply position was more normal. Unfortunately insufficient information is available to accurately reconstruct the situation then.

However there are several instances of significant over or under-supply. In most cases, demand forecasts gave advance warning of these events but no action was taken until the situation was obviously serious. The proposed machine loading system would have taken earlier action to limit future losses. For example, in 1972 one major stock-out of canvas footwear could have been substantially reduced for a saving of at least £3000 while at the same time operating with lower stocks.

#### 11.8.2.3 Conclusions

Qualitative comparisons with current practice show that the proposed machine loading system would produce acceptable mould loadings with low savings at present, but good savings in normal circumstances.

## 12.1 Introduction

As explained in Chapter 3, the resource planning function is advisory and so the associated procedures should be simple. This chapter describes briefly how to evaluate the effects of a change in resources on the production planning costs.

The chapter completes the description of the production planning solution, but is not a major part of the thesis. The results quoted here are derived from straightforward manipulation of the models of other sub-systems particularly machine loading.

Section 12.2 describes the potential benefits of new machinery and concludes that it can only be justified on the grounds of high demand. Section 12.3 considers the purchase of duplicate moulds. It concludes that these are only worthwhile if the first mould is in almost continual use.

Section 12.4 outlines how to evaluate the benefits of a change in the labour force. These tangible benefits must be offset against losses in labour relations and other costs before making any decisions. Finally, section 12.5 examines the validity of the proposals made in this chapter. It concludes that they would have improved past decisions.

## 12.2 Purchasing new machinery

Additional machinery permits increased production from that machine type and gives greater flexibility in machine loading. It should reduce shortage costs by giving greater opportunity to meet increased demand; storage costs by increasing production in season; and scheduling costs since with more mould places fewer mould changes are needed.

The capital expenditure required to obtain additional machinery is reflected in increased depreciation charges. It also increases the running costs of the factory. These costs can be accurately estimated.

#### 12.2.1 Saving in scheduling costs

A comparison of alternative machine loadings with and without an extra machine gives a reliable estimate of the saving in scheduling costs.

More simply, rough estimates can be made. An extra machine could be used solely for one manufacturing group saving associated machine changes. Since manufacturing groups are run at most five times a year, the potential saving is at most ten machine changes or fifty mould changes a year.

Alternatively several machines can be used for one manufacturing group. The value of extra mould places then depends on the demand rates for each mould. It is greater when they permit moulds to remain in use almost all the time. Practical tests for existing manufacturing groups show that the savings of this nature will not exceed one mould change a week.

At the same time the average weekly production per machine will be reduced. The freestock needed for a given rate of mould changing is proportional to the production rate per machine (see 11.2), therefore more machines permit the freestock to be reduced. The potential stock saving from an additional machine is between 10,000 and 23,000 pairs depending on the machine type.

Combining the final two effects, an extra machine could reduce scheduling costs by up to £4,000 per year, but likely savings in a typical year would be around £1,500.

### 12.2.2 Saving in storage costs

An ideal situation arises if two machine types have opposite seasons. With one spare machine of each type, the fixed labour force can produce appropriate seasonal products at a large saving in storage costs.

In theory, with the existing seasonality and its direct opposite, and with a spare machine of each type, one could reduce the average stock by 24% of the potential annual output from one machine. In practice the best match between brands gives a potential saving of 15% and the likely saving would be 8%.

There is currently a spare 'canvas' machine, so an extra 'protective' machine could save about £3,000 per year in storage costs.

### 12.2.3 Avoiding prolonged backlogs

Backlogs will arise if demand exceeds the production capacity of current machinery by more than the initial stocks. These could be avoided with extra capacity providing extra labour is available.

The value of extra capacity is the shortage cost associated with the expected backlog. The latter is extremely difficult to estimate reliably since it depends critically on the probability of exceptional demand.

The purchase of new machinery is unlikely to be justified by the saving in one year so forecasts for future years should be used. To show how robust the case for new machinery is, it is advisable to take optimistic and pessimistic demand forecasts and to calculate the return in each case.

#### 12.2.4 Economics of the purchase

The maximum saving in storage and scheduling costs from a new machine is about £7,000 a year (from 12.2.1 and 12.2.2). Even with a desired return on capital of only 10% this could not justify an expenditure of more than £70,000. New Injection Moulding machines cost much more than this, therefore any purchase must be justified mainly on grounds of meeting increased demand.

#### 12.3 Purchasing new moulds

Normally there is only one mould supplied for each size, two are occasionally available but never three. A stock projection in the product scheduling module is useful in deciding whether to purchase a duplicate mould; large shortfalls despite continuous production from a mould indicate that it is probably required.

##### 12.3.1 Duplicate mould necessary

A duplicate mould is necessary if the demand for a size cannot be met from one mould without overproduction of other products in the same manufacturing group.

In particular, if one machine is used for the manufacturing group, the maximum output from a mould is a fifth of the total production (since five moulds are used), therefore a duplicate mould is certainly needed if the sizeroll of one size is over 200 pairs per thousand sold in that manufacturing group and colour.

More generally the maximum output from a mould is lower if either that size can only be made with nearby sizes or if more than one machine runs with that manufacturing group. For example, with three machines continuously making one manufacturing group a duplicate mould

is necessary for any size taking over a fifteenth of the demand.

#### 12.3.2 Duplicate mould desirable

A duplicate mould is desirable if the first mould runs almost all the time possible. For example, if the average demand rate is 90% of the maximum production rate over a year then an exceptional order for three weeks production of that size alone, or damage to the mould taking typically three weeks to repair, would take six months to make up.

As the demand rate rises above 90% of the production rate the time to clear a shortfall rises rapidly. Random variations in the size roll can equal 5%, so that for demand rates above 95% a duplicate is advisable in case shortfalls become permanent.

A duplicate mould will prevent extended shortfalls of this nature. They are only critical during the peak season, about a third of the year, when stocks are low. A size with a high demand rate is certain to be essential to complete orders (see 10.3) so absence of a duplicate mould can delay sales of many times the shortfall.

#### 12.3.3 Economics of a duplicate mould

The capital cost of a duplicate mould is high and the expected loss is unlikely to equal the depreciation on the mould for demand rates up to 90% of the production rate.

For demand rates of over 95%, which can take over a year to clear, a shortfall a duplicate is almost certainly justified. Necessary duplicate moulds should be purchased to avoid building up permanently unsaleable stocks of other sizes (see also 8.6.1).

#### 12.4 Adjusting the labour force

The company employs 'floaters' who can be moved from department to department as the workloads vary. This gives a limited flexibility; in discussing labour variations here, I am assuming that this flexibility has already been used so further changes are by recruitment, redundancy or natural wastage.

It is company policy to avoid seasonal recruitment and layoffs on the grounds that the gain is not worth the poor labour relations and other costs involved. Therefore any changes should be planned to last at least one season and preferably longer.

The situation in the following season should therefore be considered but, unfortunately, reliable demand estimates are unlikely to be available.

##### 12.4.1 Increasing the labour force

Since overtime can be ignored (see 8.6.1), an increase in the labour force directly increases the production rate and hence the stocks. The increase is proportional to the time since the change occurred.

Determination of the machine loading by following the handbook includes the construction of a graph of immediate costs against stock (see 11.6). By projecting the stocks on a monthly basis one can determine the expected gain due to the increase in labour force.

Alternatively, if the machine loading was not determined in this manner, the cost can be estimated directly. Storage costs are proportional to stock and hence their calculation is straightforward. Shortage and scheduling costs are greatest near the end of the season where an accurate calculation is worthwhile, at other times a rough estimate will suffice.

This yields the expected gain or loss this season. The gain (or loss) for the following season could likewise be calculated, but the uncertainty in demand makes detailed calculations unnecessary and a crude estimate, as below, should suffice.

Project the likely range of stock levels at the end of the next season at the proposed production rate. If these are very high or very low further changes in the production rate are desirable at an appropriate cost. Otherwise the cost will depend on the excess of stocks over their optimum level. Using the costs derived in the machine loading, a crude estimate of the following seasons costs is obtained.

Increases in the labour force rarely harm labour relations so the cost is the recruitment and training cost. The increased wages are reflected in increased output and hence increased storage costs so need no separate calculation. Generally an increase will be worthwhile if current stocks are below the desired level, and if, after the increase, stocks at the end of the following season will not be well above their desired level.

#### 12.4.2 Decreasing the labour force

Stocks can be decreased by letting the labour force fall through natural wastage, by redundancy, or by short-time working. The latter has an immediate effect but a greater immediate cost.

The benefits of these alternatives can be found as in the preceding section. Their costs must be evaluated by management. Any redundancy or short-time working will harm labour relations; this is particularly so if the labour force has recently been increased, since this implies poor management.



Generally natural wastage or a small redundancy are better with advance warning of a downturn in business. Short-time working is better if the downturn has already occurred and stocks are high.

#### 12.5 Validity of these proposals

In recent years there have been various purchases of machinery and moulds and several alterations of the labour force. Had these proposals been in operation all actual decisions would have been taken plus one or two more. Detailed comments are made below.

##### 12.5.1 New machinery

Recent demand for protective footwear has exceeded the production capacity. The likely benefits of extra capacity do not justify a new machine. When the chance arose to purchase a second-hand medium size machine, the likely benefits exceeded its cost and it was purchased.

##### 12.5.2 Duplicate moulds

Demand for four sizes of one type of protective boot regularly exceeds 95% of the production capacity. Duplicate moulds have recently been purchased for three of these sizes but not the fourth which has an almost identical demand. As a result there have been prolonged shortages of this latter size; these could be avoided with an additional mould.

##### 12.5.3 Altering the labour force

The labour force has decreased once and increased once in the past three years. Both changes reduced future costs and were therefore advisable. Greater savings would have been made had the changes occurred earlier, but other factors may have caused the delays.

13.1 Introduction

Most decisions are made in a state of partial ignorance with various unknown factors. A forecast is generally a single figure estimate of an unknown variable, although its probable range or even its distribution may be given. The requirements for decision making are discussed briefly in Section 13.2; in this chapter I assume that forecasts specify the expected value and standard error\* of an unknown variable.

Subjective forecasts are made on the basis of hunches or personal experience. These are particularly useful for predicting changes in a pattern. Quantitative forecasts, as in this chapter, are produced as a function of already known variables. They rely on the continuation of an assumed or identified pattern.

Often the unknown variable is the next value in a series called a time series, where the forecast is to be made from earlier values of the series. This is called time series analysis and has been applied to such series as the annual consumption of electricity, the maximum daily temperature or, as here, the monthly sales of a product.

Section 13.3 discusses various techniques of time series analysis. It stresses that the value of a forecast depends not on its sophistication, but on how well it fits the situation. The effectiveness of various techniques in forecasting sales of typical products made by Dunlop Footwear is presented in Section 13.4, where a suitable forecasting system is proposed.

\*The standard error is a statistical estimate of the variability of the demand, calculated like the standard deviation.

There is often reason to believe that the sales of a product may be related to general economic conditions, in particular to 'trade cycles'. Econometric analysis is the search for such relationships. One particularly seeks 'leading indicators' which vary ahead of the relevant sales and can be used to forecast them. In section 13.5 a trade cycle model of the footwear market is compared with an explanatory model.

The situation at Dunlop Footwear seems better explained by the latter model once allowance is made for the weather. Its effects on the demand for protective footwear are discussed in Section 13.6. Finally, Section 13.7 suggests a model for the demand at Dunlop Footwear. It then gives proposals for immediate and long term action.

### 13.2 A background to forecasting at Dunlop Footwear

#### 13.2.1 Forecasting requirements

Demand forecasts are needed at three levels for production scheduling; overall for long term budgeting, at product level several months ahead for machine loading, and at size level for mould scheduling.

At present, product forecasts are made subjectively for the management plan; these are revised twice in the year. An objective forecasting method which revises the forecasts monthly is proposed in this chapter.

Ideally, the forecasting method should minimise the costs of the associated decisions, but these can rarely be calculated. The standard approach, which I have followed, is to select a forecasting method which minimises the standard error of the forecast on the assumption that larger errors are more costly.

### 13.2.2 Data available

Sales data is available at each level. Three years' data are available by size, and sales from 1961 at manufacturing group and industry levels. The data has several known imperfections. It relates to sales, not demand; the products have changed over the period; and the statistics have been altered for political reasons (e.g. to improve a bad year). These imperfections cannot reliably be removed. Nevertheless, a substantial amount of information is available. There is sufficient to derive forecasting measures from early data and test them on later data.

A comparison of the errors of the management forecasts with those of a simple forecast suggests that analysis should be worthwhile (see table 18). Visual analysis of the data shows that the sales have a stable seasonality with apparently random fluctuations in annual sales.

### 13.3 Time series analysis

A simple forecast of the next value in a series, knowing only the earlier values, is the latest value. An alternative is to pick a constant, say the mean of early values in the series, as the forecast, ignoring subsequent data.

A forecasting method used in practice should perform on average at least as well as these, so I am using the above methods as standards for comparison.

If there is no pattern in the data, then no forecast should be better than the above forecasts. An improvement relies on a pattern in the data. Since an appropriate pattern may not be present, it is poor practice to apply an arbitrary forecasting method without either a

prior reason to believe it is appropriate or justification from testing it on earlier values.

Many text books recommend a particular method of forecasting for any application without justification. This can lead to poor forecasting. For example, in expanding markets it is advisable to use a method which projects any trend rather than assuming a constant sales rate.

#### 13.3.1 Exponential smoothing

A commonly proposed technique is called exponential smoothing. This assumes that a proportion of the variation in the data about its current level is absorbed into the new level of the series.

The new forecast is given as the old forecast plus  $A$  times the error in the last forecast, where  $A$  represents the proportion of the total variation which is due to changes in level.

In practice exponential smoothing is used when a series varies randomly about the current level, and less frequently moves to a completely new level. It is not appropriate if a series has a fixed long-term mean or if it has a definite trend (although trend-correction can then be applied).

#### 13.3.2 The Box-Jenkins approach

Box and Jenkins (65) provide a thorough approach to time series analysis (although not as an introduction to it). They assume that there is an underlying pattern to the variations in the series which they seek to uncover. (Mathematically, they assume that a series can be regarded as the output from a linear filter whose input is white noise).

They employ three stages in model building; identification of an appropriate form of model, estimation of the relevant parameters, and validation of the model. Their method of identification uncovers most standard models and many others; estimation is based on finding the forecast with least standard error, and validation involves studying the residual errors for any patterns. Basic tools in this are the auto-correlation and partial auto-correlation functions.

Full application of their (expensive) techniques was not worthwhile for the sales series at Dunlop Footwear since the assumptions are not fully justified and the estimates of the auto-correlations with seasonal data would be unreliable. However, I applied their techniques where suitable to identify, estimate for and check various models.

#### 13.3.3 Adaptive forecasting

The general Box-Jenkins model assumes the underlying model is static. Adaptive forecasting methods are appropriate when the parameters of the model may alter. The changes in the forecast are small if the errors are low and random but, if the errors are consistently of one size, it is assumed that the background model has altered and larger corrections are made to the forecast until equilibrium is restored.

#### 13.3.4 Bayesian forecasting

An interesting extension to adaptive forecasting was provided by Harrison and Stevens (66). They assume three possible states; random variations, changes in level and changes in trend. Each of these is given a 'prior' probability; the actual series is used to calculate current probabilities of these conditions and hence forecast for the future.

A Bayesian approach is also used by Murray and Silver (64) in seasonal forecasting. They assume that the sales of a product equal the seasonality times the annual sales rate plus a random factor. Initial estimates are made of the annual sales rates. These are corrected after the monthly sales figures become available according to the relative variances of the estimates of the annual sales rate and the random factors. This approach is similar to one proposed in Section 13.4.

#### 13.3.5 Forecasting seasonal time series

The standard method of forecasting seasonal time series is to first remove the seasonality by division giving the current annual sales rate. The resulting time series can be forecast by standard techniques and the seasonality subsequently restored (see for example Brown (67)).

An alternative approach was described in the last section. Other authors propose forecasting the sales over the whole season and adjusting this forecast as the season progresses. Hertz and Schaffir (68) suggest scaling up the sales-to-date to get a forecast for the whole season.

Chang and Fyffe (69) propose an interesting variant of exponential smoothing. They assume that initial estimates of the seasonality and total demand are available, and that fluctuations around these are random and independent with known variances for each month and for the whole season. After each month's sales, the forecast of the sales in the season is revised by a multiple of the difference between the actual and expected sales in the month. This multiple reflects the information that can be gained from recent demand and is highly sensitive to the ratio of monthly variance to total season variance.

This method is similar to one proposed in section 13.4.3.

#### 13.4 Forecasting sales at Dunlop Footwear by time series analysis

##### 13.4.1 Introduction

My investigations into sales forecasting covered all P.V.C. footwear made by Dunlop (plus a few other products). My objective was to produce a simple but reliable forecasting method for forecasting from one month to one year ahead which would be applicable to all such products.

In reporting the results of various forecasting techniques, four typical products or manufacturing groups were selected. Three of these are protectives, and the first of these is a manufacturing group. Results for other products are similar to the results reported here.

The data from which these forecasts were made is supplied as appendix 5; the figures have been scaled up or down uniformly for commercial reasons. This does not affect the relative performance of different techniques.

Section 13.4.2 reports on various annual sales forecasts. Section 13.4.3 proposes a method of monthly sales forecasting. Sections 13.4.4 and 13.4.5 compare various forecasting methods on forecasting peak season and next month's sales. Section 13.4.6 discusses forecasting at size level. Finally section 13.4.7 recommends acceptance of the proposed forecasting method. (Note that all forecasts are actually sales forecasts although one is primarily interested in demand.)



#### 13.4.2 Annual sales forecasting

Sales of all Dunlop products vary seasonally, but there are no systematic annual variations, therefore standard techniques should be appropriate for forecasting annual sales.

Table 18 shows the standard errors of a variety of techniques for forecasting the annual sales. With the exception of the management forecasts, all forecasts are made 12 months ahead. The management plan forecast is made 15 months ahead, and the March review 10 months ahead.

The most accurate method of forecasting of those selected is the mean sales over the period; this has an average weighted error of 62. However, the mean sales are unknown in advance, so this forecast cannot be used in practice.

If a constant value is to be used as the forecast, an obvious choice is the mean demand in the preceding years. This is one of the worst forecasting methods tested with an average error of 121. In contrast, forecasting that this year's sales will equal last year's sales is fairly reliable with an average error of 70.

This suggests that there is no fixed level for the demand but that it fluctuates freely from year to year. Exponential smoothing is an appropriate forecasting method in such circumstances, the smoothing coefficient can be adjusted to alter the emphasis placed on recent information.

For individual products table 18 shows that the optimal coefficient varies between 0.5 and 1.0, but there is insufficient evidence to suggest there are significant differences between the products. The

Table 18     Standard errors of various yearly forecasts

	Protective			Canvas	Weighted Error
	A	B	C	D	
Mean demand	599	681	391	552	469
<u>Forecasting method</u>					
Mean	52	79	58	106	62
Constant	112	190	126	119	121
Last year's sales	72	113	74	66	70
Exponential smoothing					
coeff <sup>t</sup> 0.2	93	168	85	121	97
"      0.5	63	112	60	90	68
"      0.7	60	108	61	79	65
Monthly exp. smoothing	68	109	61	66	65
Trend corrected forecast	85	125	55	101	71
Management Plan <sup>*</sup>	64	419	113	27	126
March Review <sup>*</sup>	23	314	83	30	90

\* Based on results from a restricted period. The ratio to exponential smoothing is correct, but not the ratio to the mean demand.

best overall coefficient is 0.7 which gives an average error of 65, or around 14% of the annual demand; it is never significantly worse than the best coefficient for any product.

More complex forecasts involve correction for any trends in the demand. A visual analysis of the data shows no trends, and a forecast with mild trend correction is slightly worse than the best exponentially smoothed forecast. Other complex forecasts were tried on one or more of the products. There was no 'a priori' reason to believe any of these were appropriate and none consistently performed well.

The final calculated forecast in table 18 is a monthly forecast described later which is very similar on an annual basis to exponential smoothing with coefficient 0.7 and gives similar results.

The management plan and March review forecasts are only available for part of the period. To give comparable results, the figures have been adjusted to the full period so that the ratio of their errors to that from exponential smoothing (coefficient 0.7) is correct.

The results reveal that the management forecasts generally have a low accuracy, except for the canvas product. Here they correctly predicted a fall in demand for reasons which techniques based on past demand could not foresee.

In conclusion, the most accurate single forecasts are based on exponential smoothing where a monthly or annual forecast can be used. The results for the canvas product suggest a combined management/calculated forecast might be most appropriate.

### 13.4.3 Monthly forecasting techniques

When forecasting seasonal time series, some method must be found for incorporating the seasonality. For the products made by Dunlop, each month takes a fairly constant proportion of the total demand so the seasonality is multiplicative. This means that the best current forecast of sales in any period is 'the forecast annual sales rate multiplied by the appropriate seasonality factor' (which must also be forecast). Note that this assumes no trend in the demand.

The monthly forecasting problem therefore separates into two parts; forecasting the annual sales rate, and forecasting the seasonality factors.

#### 13.4.3.1 Forecasting the seasonality factors

The seasonality factors fluctuate from year to year but also vary slowly with time. A simple forecasting technique should be appropriate for estimating the seasonality factors.

At the end of each year, I suggest that the seasonality factors for each month are revised using the formula below (which is exponential smoothing with a coefficient of 0.2):-

$$\begin{aligned} \text{New seasonality factor} &= \text{Old seasonality factor} \times 0.8 \\ &+ \text{Seasonality this year} \times 0.2 \end{aligned}$$

Using this formula, a change in seasonality was successfully detected and coped with for product D. However to simplify testing, all forecasts in later sections were made with a constant set of seasonal factors. For product D which has the largest change in seasonality this simplification increases the forecasting error by only 3%; this justifies the use of a simple approach.

#### 13.4.3.2 A proposal for monthly forecasting of the annual sales rate

The 'standard' method of forecasting seasonal time series places equal weight upon the percentage variation in each month. This is reasonable if the seasonality is low, but not if the expected demand in one month exceeds eight times the demand in another month as here. A 50% increase in demand in the former month would be highly significant, but in the latter month it could be irrelevant. (Note in table 19 that the standard approach is 15% less accurate in forecasting peak season sales than the proposed approach.)

In an appropriate forecasting system, the weight placed on any variation from the expected demand should depend on the probability of such variations. The 'information content' of any month's demand could be defined as the variation from expected demand divided by the standard error for that month.

The correction to the forecast of the annual sales rate could then be a constant multiple of the 'information content' for that month. This is the basis of the system proposed by Chang and Fyffe (see 13.3.6).

The standard error of each month's demand was found by analysis for a wide variety of products to be proportional to the one-third power of the seasonal factor. (December and January are always very variable months implying sales may be transferred from one year to another.) An appropriate forecast is therefore:-

New annual sales rate = old annual sales rate + constant  $\times$   
(sales last month - forecast sales last month)  $\div$  seasonality <sup>$\frac{1}{3}$</sup>



months. Stocks are lowest at the end of the season, therefore the most critical forecast is the forecast of peak season demand; for protective products the peak season is September to December.

The seasonality is reasonably constant from year to year; typically just over half the demand for a product occurs in the peak season. The peak season demand can therefore be forecast by taking the best estimate of the annual sales and multiplying by the appropriate factor.

Table 19 shows how such forecasts gradually improve in accuracy as one approaches the peak season. The forecast one month before the season is only 10% better than one made at the beginning of the year, but a retrospective forecast is a great deal better. (The errors in the retrospective forecasts are mainly due to changing seasonality.)

Table 19 also shows that last year's peak season sales are as reliable an indicator at the beginning of the year of this year's peak sales as the seasonality multiplied by the best forecast of this year's annual sales. However scaling-up the sales to August is an unreliable estimate of the peak season sales, as is the 'standard' method.

Even one month before the peak season, the sales forecasts are most unreliable with an average error of around 20% per product. The error in the aggregate sales of one machine type is lower at about 10%. In summary, one learns little about the peak season demand early on in the season.

#### 13.4.5 Forecasting sales one month ahead

Comparisons on an annual and peak season basis have already given favourable results for the proposed forecasting system; table 20

Table 19      Standard errors of forecasts of peak season sales

		Difference between				
		Protective			Canvas	Weighted Error
		A	B	C	D*	
Mean peak season sales		284	364	206	134	215
<u>Forecasting method</u>	<u>Month</u>					
Previous season sales	Dec	29	71	61	28	43
Annual forecast x seasonality	Dec	33	69	54	40	43
"	Feb	29	64	55	38	42
"	Aug	27	61	52	36	39
above as % of sales		10%	17%	25%	27%	18%
"	Retro- spective	17	35	28	30	24
Year-to-date scaled up	Aug	44	69	59	36	47
'standard' monthly fore- cast x seasonality	Aug	28	82	64	29	46

\* Not peak season for canvas products



shows that it is also good at forecasting next month's sales.

The results show that the proposed system gives the best results of those methods tested. However there is only a 25% difference between the best and worst forecast - this suggests that most of the variation is truly random and little further improvement is likely, a conclusion borne out on detailed examination of the sales data.

#### 13.4.6 Forecasting demand at size level

The preceding discussion has concerned demand at product, manufacturing group and machine type levels. The demand for each size of a particular product is forecast as the total demand multiplied by the sizeroll for that size.

Fortunately it is not necessary to establish elaborate systems for forecasting the sizeroll since it varies only slowly with time and since mis-estimates are automatically corrected for on rescheduling. The safety stocks provide cover against variations in sizeroll.

It is sufficient therefore to check the sizerolls twice a year, using recent demand or future orders, if there are many, plus advice from the sales department to adjust them.

#### 13.4.7 Conclusions on sales forecasting at Dunlop Footwear

Several experts have examined sales forecasting of Dunlop Footwear products and have tried various techniques. All agree that there are bound to be considerable errors in any computed sales forecast. Their conclusions have been broadly similar to mine, although they have found no generally applicable and reliable forecasting method.

My conclusions are that short term forecasts (a month ahead) are

Table 20

## Standard errors of monthly forecasts

	Protective			Canvas	Weighted Error
	A	B	C	D	
Mean monthly demand	50	57	33	46	39
<u>Forecasting method</u>					
Proposed method (Current annual rate x seasonality)	10.2	17.9	13.1	12.0	11.7
'Standard' method (see 13.4.3)	10.7	19.8	13.8	12.4	12.4
Seasonality x better of mean or last year's sales	10.3	18.0	13.9	12.4	12.0
Corresponding month last year	12.8	24.7	17.3	15.2	15.2
Adaptive forecasting	11.9	23.4	-	-	

bound to have large percentage errors. Any reasonable technique should give similar forecast accuracy providing the estimates of seasonality are reliable.

As the forecast horizon moves further away and the period to be forecast increases, the random variations in demand become less important and the forecasting method becomes more important.

A seasonally-adjusted form of exponential smoothing proposed in section 13.4.3 gives good forecasts for all products examined.

For any one product, it is rarely much worse than the best technique for that product, and overall it performs better than any other technique. I therefore propose that this forecast, which is simple to calculate, should be tested against current practice to show the value of objective forecasting techniques.

### 13.5 Models of the footwear market

Consumers' expenditure on footwear has grown fairly steadily in real terms since 1955 (Diagram 28). In this period, manufacturers' sales have fluctuated with slumps about every fourth year (see diagram 29); this is partly due to changing import levels but mainly to differences in the stocks held by retailers and wholesalers.

Various explanations of this behaviour have been proposed. A common belief, expounded by Bouch and Manning (70), is that 'trade cycles' cause the footwear cycle. An alternative view held by Leicester (71) is that the retailers' ordering policies cause this cycle. These views need not be contradictory but may stress different aspects of the problem. Leicester's model has the advantage that it enables a numerical prediction of sales to be made.

Diagram 28

ANNUAL CONSUMER EXPENDITURE ON FOOTWEAR  
(1961 - 1971)

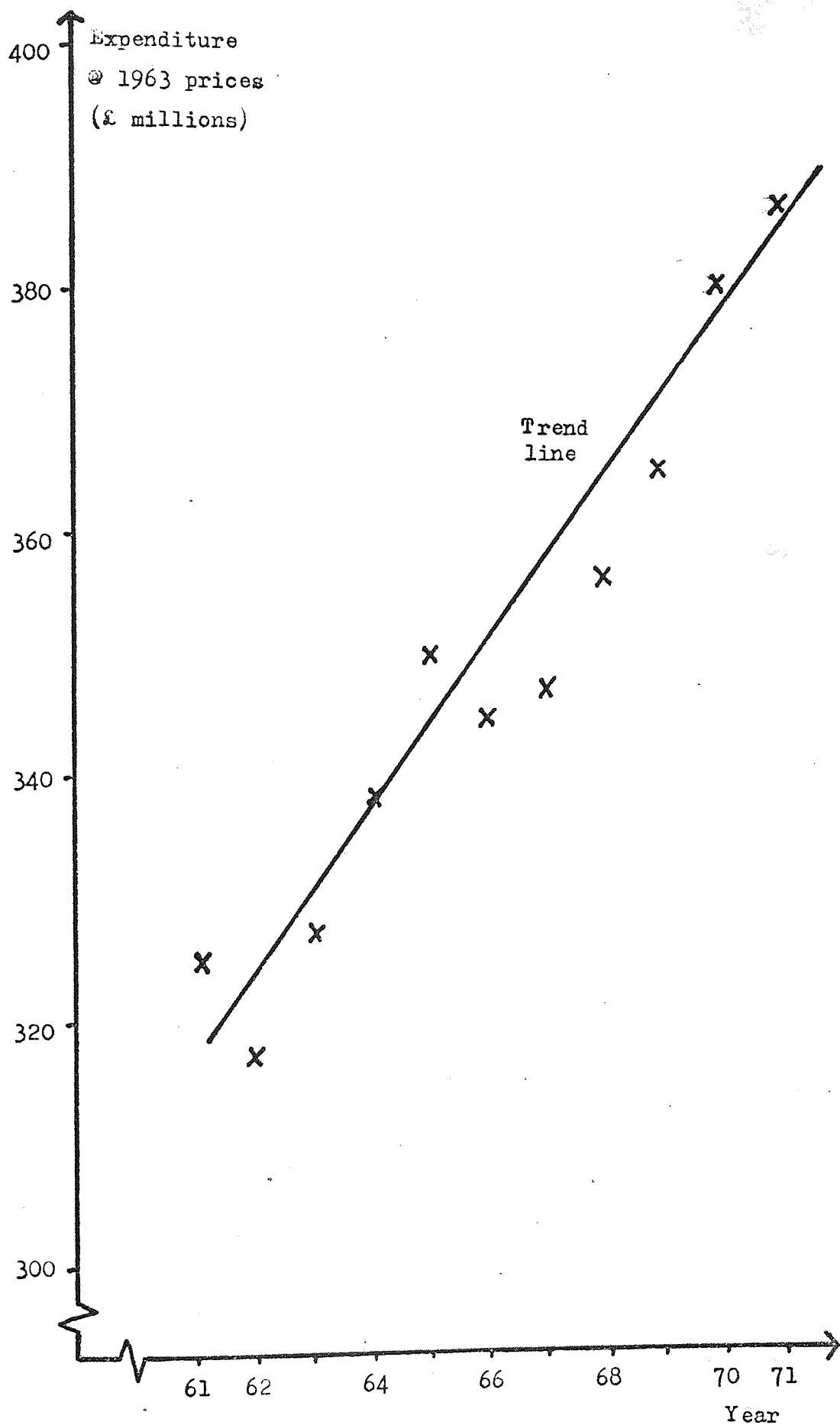
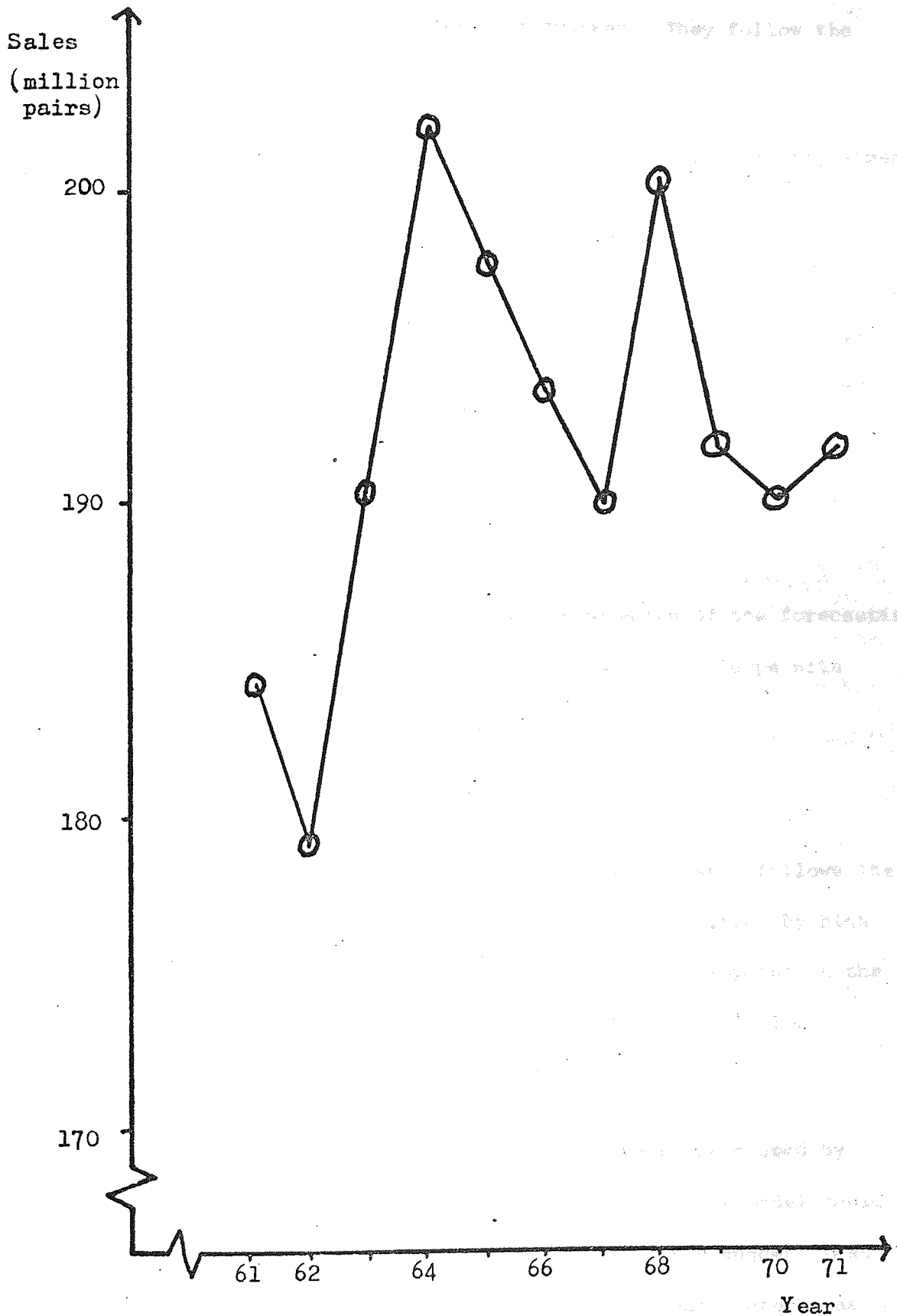


Diagram 29

ANNUAL SALES BY U.K. FOOTWEAR MANUFACTURERS  
(1961 - 1971)



#### 13.5.1 Leicester's model

Leicester assumes that the cyclic behaviour is caused by the retailers' budgeting methods. He suggests that shoe retailers budget six months ahead using their knowledge of the last quarter. They follow the following principles:-

1. The budgeted purchases equal the budgeted sales plus an adjustment to correct stocks to their budgeted levels.
2. They budget for a constant growth in sales.
3. Stocks are intended to service their sales, but retailers rely also on manufacturers. With long delivery dates, the budgeted stocks are high.
4. In good times retailers increase their orders and vice-versa.

Leicester claims that this model represents 99% of the variation in retailers' deliveries. It reveals the inadequacies of the forecasting methods used in the industry, and predicts booms and slumps with reasonable accuracy.

#### 13.5.2 The 'trade cycle' model

The alternative hypothesis is that the footwear industry follows the ups and downs of other industries (70). This is justified by high correlations between such measures as output or unemployment in the shoe industry and in the U.K. generally and also by a similar behaviour of the share prices.

The authors suggest that slumps in the trade cycle are caused by government restrictions on credit (which in Leicester's model could cause retailers to make pessimistic revisions). They suggest that information about demand should be relayed to the manufacturer as

quickly as possible and that businessmen should not over-react when the economic climate changes. This solution would be applicable for either model.

#### 13.5.3 Application of these models to Dunlop Footwear

Dunlop Footwear sells in the protective and casual sectors of the footwear market. These behave similarly to the overall market, except for light wellingtons which are very weather-related. However, Dunlop's sales have relatively little in common with the trade cycle. Econometric analysis reveals little more than was found by Bouch and Manning (70). Individual sectors reach their peaks and troughs in different years, suggesting that the trade cycle model does not explain everything.

Each cycle has had the property that retailers' and wholesalers' orders increased as delivery dates lengthened and then fell off rapidly as their stocks increased and manufacturers' became able to meet their orders. This suggests that Leicester's model for retail purchases is valid in sectors of the footwear market. Unfortunately the detailed past information on consumers' purchases and on delivery dates needed to test this model in individual cases was unobtainable.

#### 13.6 Effects of the weather on sales

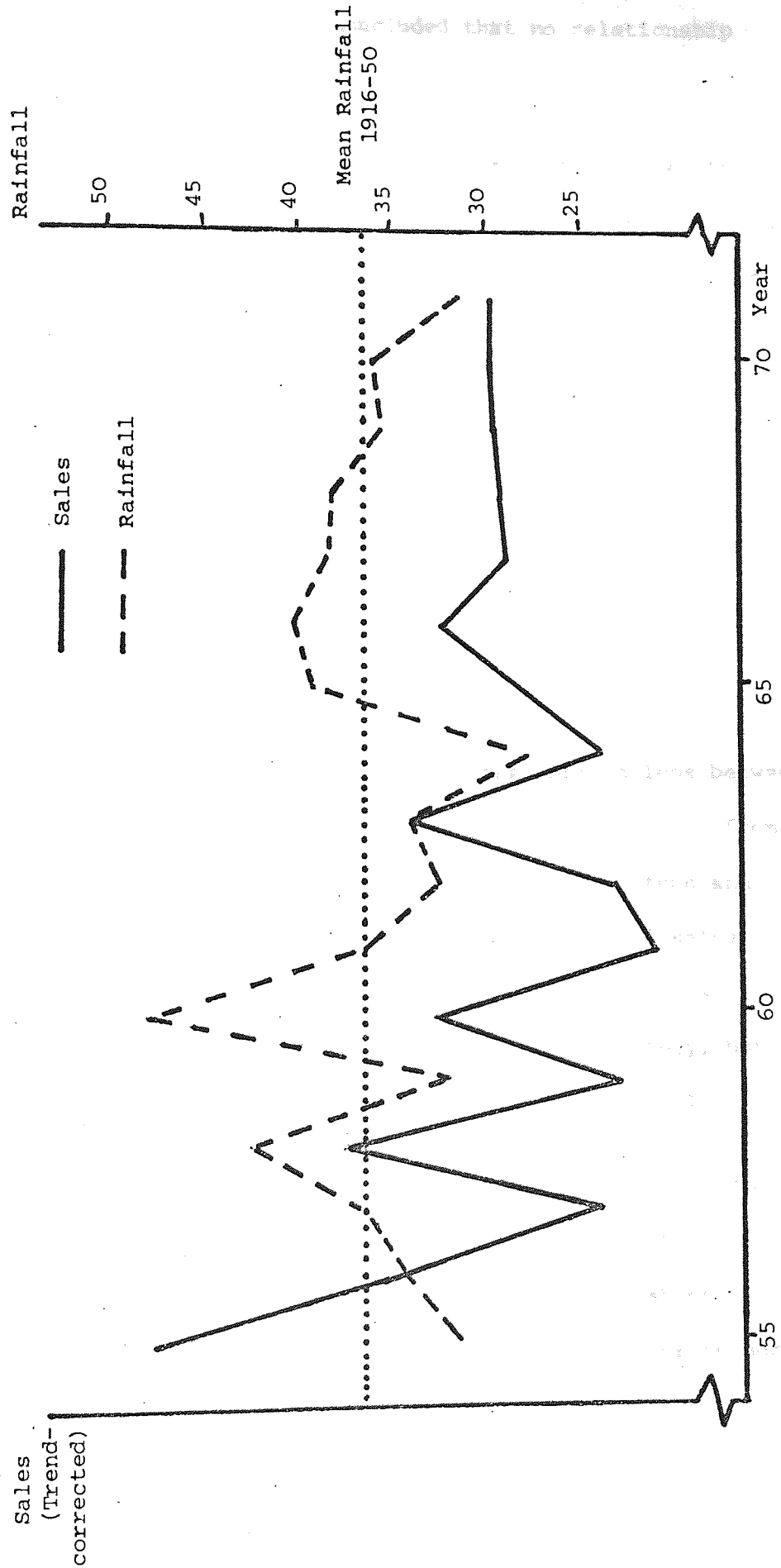
Much of the footwear sold by Dunlop Footwear is designed for specific outdoor conditions. It is reasonable to expect sales to depend on the weather which probably accounts for most of the sales seasonality.

##### 13.6.1 Protective footwear

Protective footwear, such as wellingtons, is designed to protect one from the weather and is mainly worn in winter months. It is

Diagram 30

Comparison of the annual rainfall and trend-corrected  
U.K. manufacturers' sales of protective footwear  
(Note trend-correction is to make comparison clearer)





reasonable to expect the demand to depend on the rainfall; however various studies by the Company had concluded that no relationship could be found. (See diagram 30.)

This conclusion seemed strange to everyone. I therefore tried to determine circumstances under which people would buy protective footwear. It was generally felt that the ground conditions, rather than the weather, were important so I hypothesised that protective footwear was bought in muddy or slushy conditions.

I then had to measure these conditions and decided that major factors were the weather and time of year, although the ground temperature is also relevant. For example, late spring and summer rainfall does not generally cause any mud, while autumn and winter rainfall does, and lying snow becomes slushy.

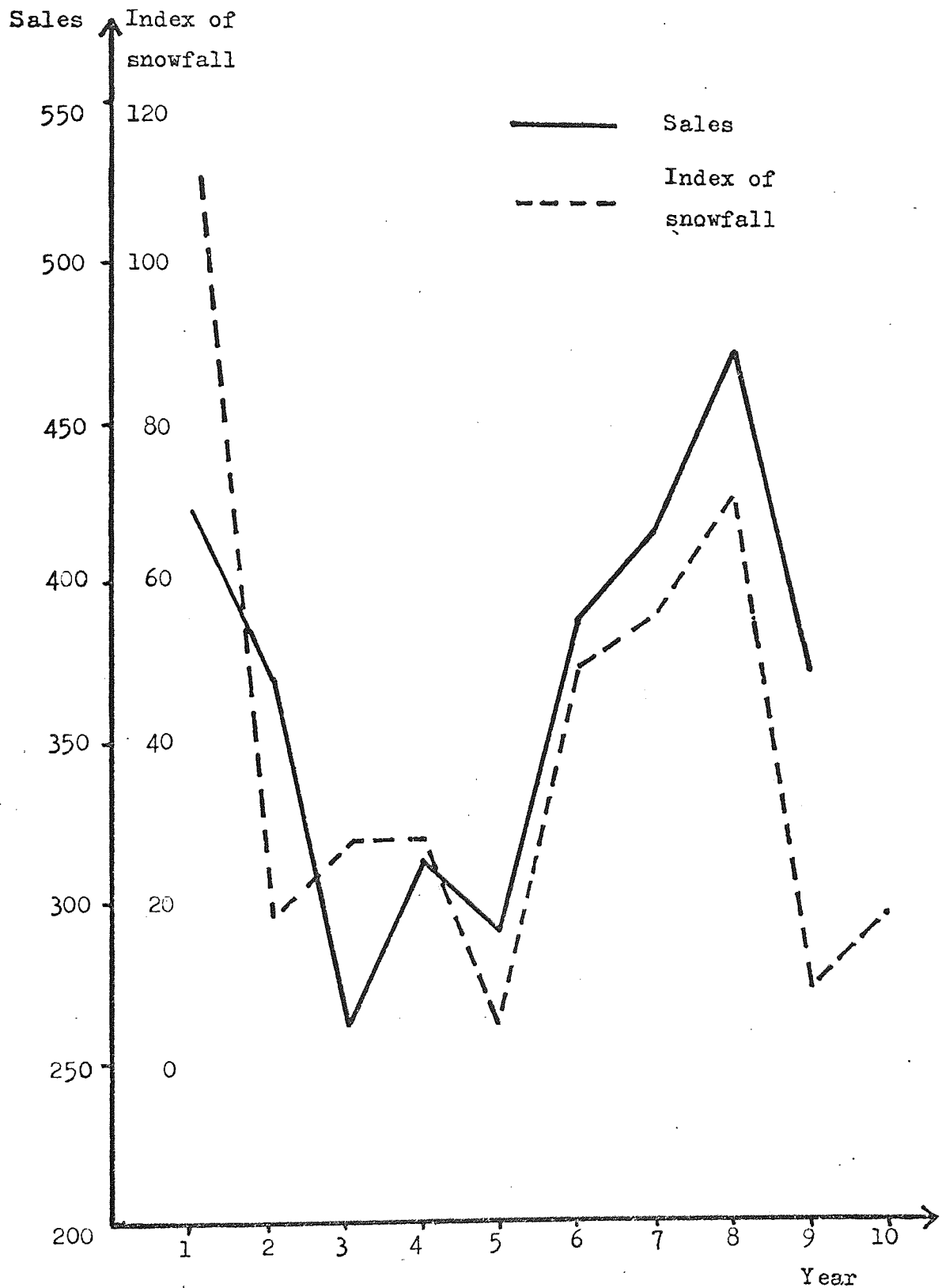
Dividing the year into quarters, I calculated the correlations between sales of a major product, rainfall and snowfall in each quarter from 1962 to 1968. These showed significant correlations in autumn and winter but also higher correlations between bad weather and sales about nine months later. This suggests that consumer purchases depend on bad conditions; some retailers re-order immediately, but most adjust their orders later as implied by Leicester's model.

The division into quarters was arbitrary; in later studies the year was split into three parts since this seemed most appropriate. On extending the investigations to 1971, I found the relationships continued to apply (see table 21 and diagrams 31 to 34); furthermore, they also applied to other protective products, including some industrial products.

In conclusion: Consumer purchases of protective footwear depend on

Diagram 31

A COMPARISON OF THE SNOWFALL JAN TO APRIL AND  
THE PEAK SEASON (SEP TO DEC) SALES OF PRODUCT B



Index equals days of falling snow  
plus twice days of lying snow(slush)

Diagram 32

A COMPARISON OF LATE SUMMER RAINFALL (JULY TO SEP)  
AND SALES OF PRODUCT B NEXT SPRING (JAN TO APRIL)

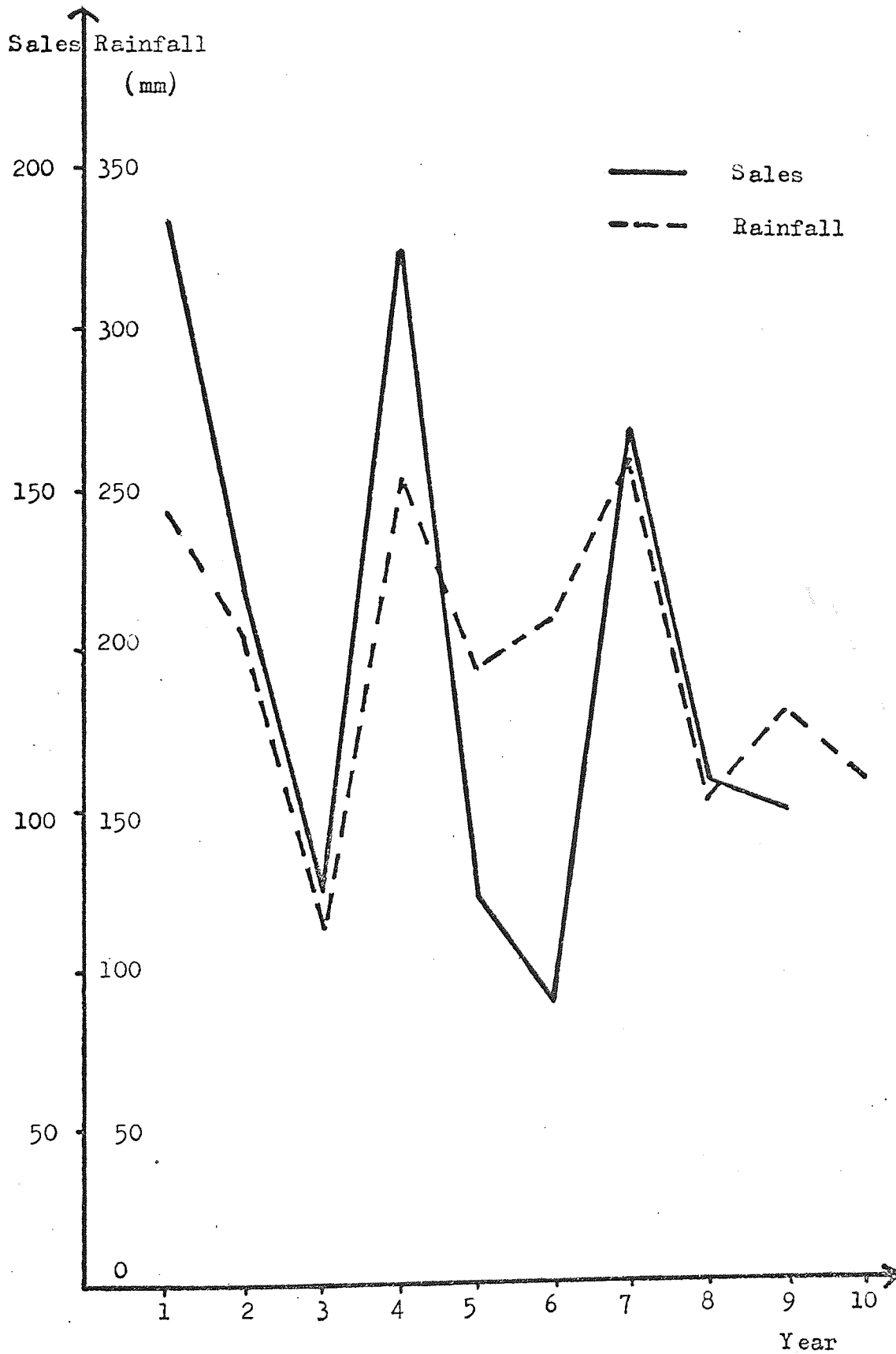
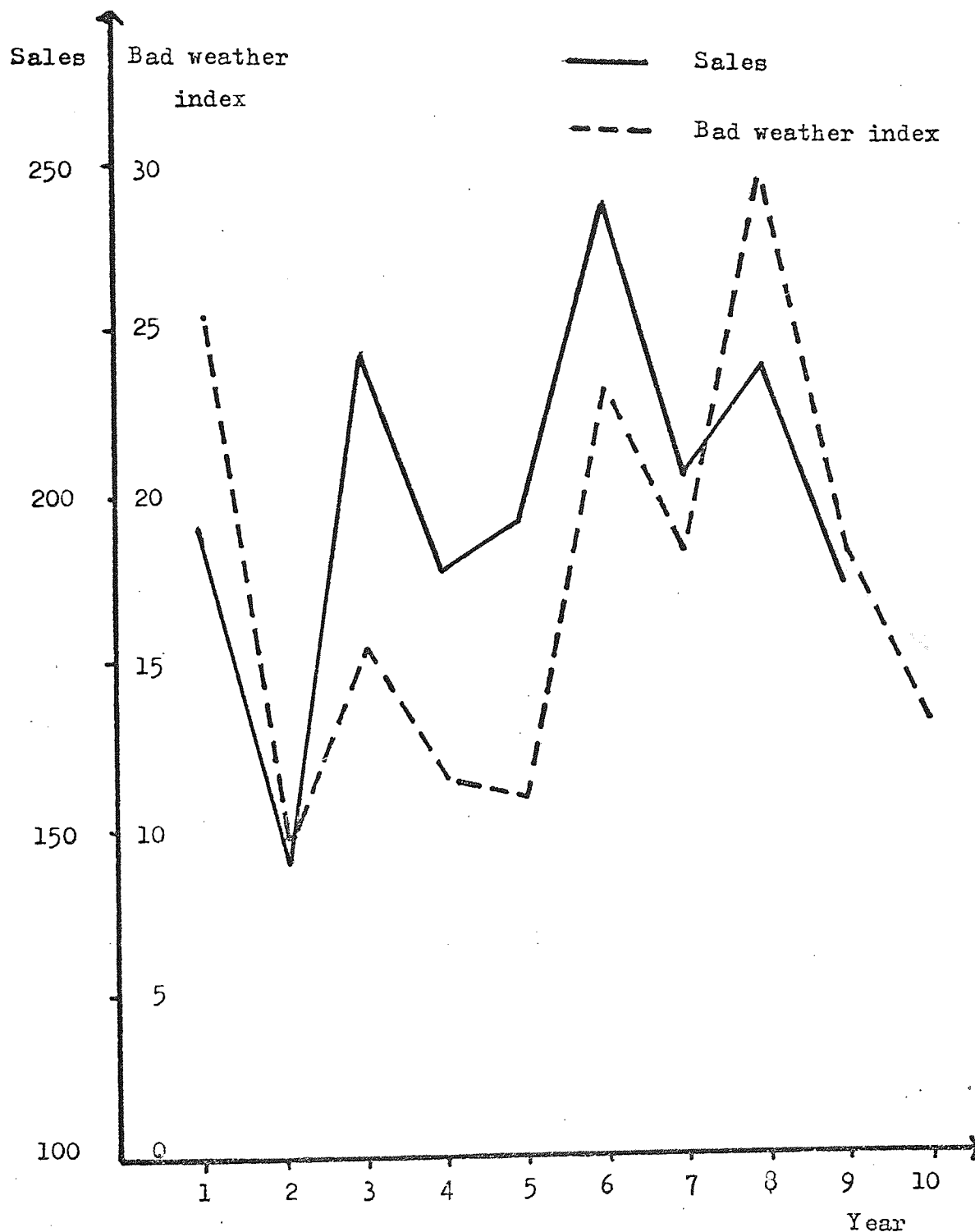


Diagram 33

AN INDEX OF EARLY WINTER (OCT TO DEC) BAD WEATHER  
COMPARED TO SALES OF PRODUCT B NEXT MAY TO AUGUST



Bad weather equals  $\frac{1}{20}$  rainfall October to mid-November (mm)  
plus days of falling snow  
plus twice days of lying snow by end December

Diagram 34

HOW WEATHER CORRECTION REDUCES THE VARIATION  
IN ANNUAL SALES FOR PRODUCT B

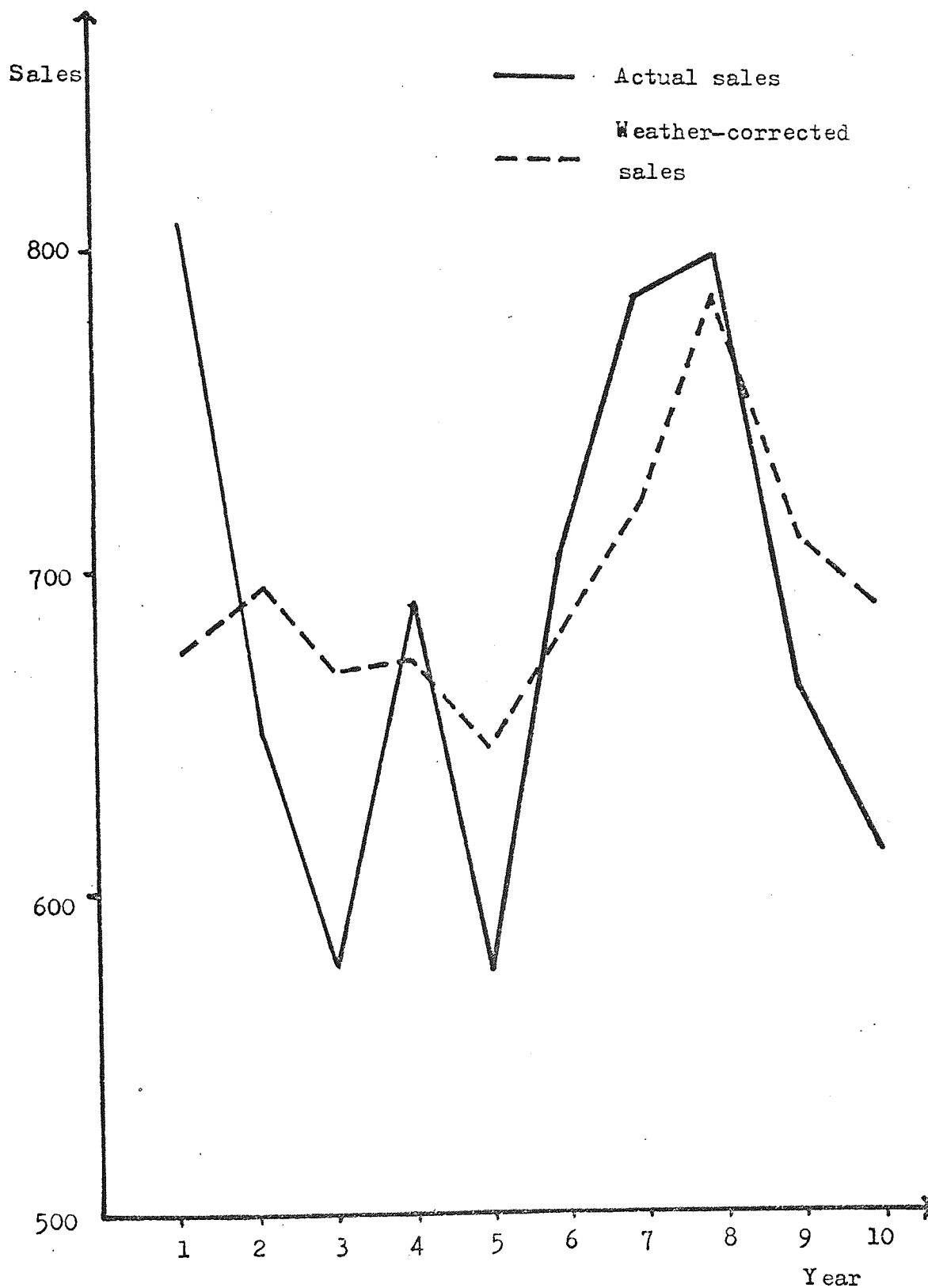


Table 21    Correlations between bad weather and sales of  
protective footwear

	Rain in Year	Snow Jan-Apr	Rain July-Sept	Rain & snow Oct-Dec
<u>Product B</u>				
Total sales	-.17	.59		
Sales Jan to April		.61		
Sales May to August		.18	.81*	
Sales Sept to December		.74*	-.36	.10
Sales next Jan to April			.79*	-.39
Sales next May to August				.58
<u>Product E (Childs only)</u>				
Total sales	.21	.13		
Sales Jan to April		-.15		
Sales May to August		-.27	.77*	
Sales Sept to December		.54	.24	0
Sales next Jan to April			.68*	.10
Sales next May to August				.01

\* Significant at 5% level

ground conditions.

These conditions can be measured in terms of the season, rainfall and snowfall. Many orders from retailers or wholesalers occur nine months after the original demand. Therefore, estimates of future demand can be improved by a knowledge of past weather conditions.

#### 13.6.2 Other products

For non-protective, mainly canvas, footwear, I could find no significant relationships between sales and any type of weather, except that sales are consistently greater than in the summer. This result is reasonable since children, who are the major wearers of canvas footwear, tend to wear it for most of the summer regardless of the weather.

### 13.7 Conclusions

#### 13.7.1 Demand model

Verbal reports on the responses of retailers (and wholesalers) to varying delivery dates combined with the evidence of a nine-months delay in the demand for protective footwear, give strong support to Leicester's model of the footwear market with the following additions:

5. Consumer demand is seasonal with an established seasonality; for protective footwear demand depends on the ground conditions.
6. Retailers' budgeted stocks vary seasonally so that orders will rarely be placed for delivery in the off-season.

#### 13.7.2 Long-term proposal

The information needed to employ this model to sectors of the market

is not currently available. Information on retail and wholesale stocks would be extremely valuable. It could be used to validate the model and hence predict from it. It would be particularly useful to know how demand falls off as delivery dates are shortened so that advance action may be taken to reduce overstocking by the manufacturer at this stage in the cycle.

#### 13.7.3 Immediate proposal

Since information on retail stocks is not available, the current demand must be estimated from past orders. I suggest using the best forecasting method identified in section 13.4.3. This basically identifies the underlying annual sales rate by a modified form of exponential smoothing. .

For protective footwear, the estimate up to six months ahead can be improved by including knowledge of recent weather conditions.

Subjective corrections can be made to these forecasts to correct for the assumed effects of retail stocks and manufacturers' delivery dates.



### 14.1 Introduction

This chapter is closely linked to chapter 15. It reports on the proposed form of the production planning system, while chapter 15 reports on actual implementation.

Since the proposals altered during the project the distinction is not clear-cut. To clarify the situation, the proposals are presented as they were in May 1974 when the details were finally settled. Very little was altered from the outline proposals made in July 1973.

Section 14.2 presents the proposed structure of the system including details of the parts to be performed manually and the parts to be computerised. The next four sections describe the operation of each module in turn, namely 'Sales Forecasting' in 14.3, 'Machine Loading' in 14.4, 'Product Scheduling' in 14.5 and 'Resource Planning' in 14.6.

Implementation was planned to take place in three stages. These are described in order in section 14.7. Finally, section 14.8 mentions possible developments to the system after the project is finished.

### 14.2 Structure of the production planning system

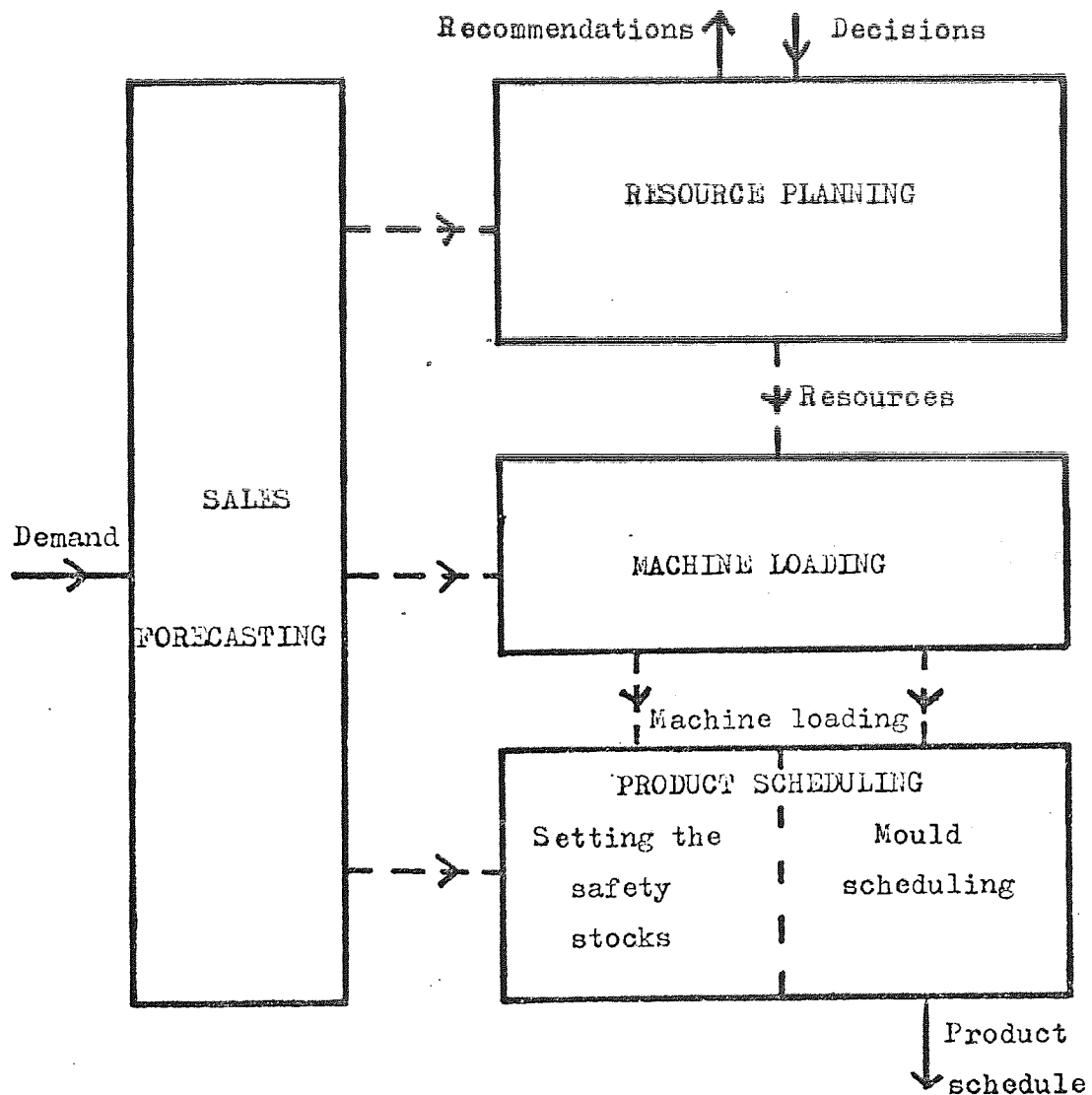
The theoretical structure of the production planning system was provided in chapter 5 (repeated in diagram 35). The constituent parts or modules are sales forecasting, resource planning, machine loading and product scheduling.

Resource planning has an advisory rôle which only affects planning in the medium to long term. It can therefore be performed separately from

Diagram 35

THE PRODUCTION PLANNING SYSTEM module separately.

(see Diagram 11)



the other parts so it is convenient to consider this module separately.

#### 14.2.1 Use of the computer

The company has a small computer which can be used to perform appropriate parts of the scheduling system. If everything was straightforward, the planning could be wholly computerised. Earlier chapters emphasise that many exceptional conditions arise in practice. Following my approach first stated in chapter 6, which stresses the need for the schedule to be feasible, I decided that a mixture of computerised and manual systems was most appropriate. The computer should be used where routine calculations following a standard algorithm are required. Decisions should be made manually where judgement is required or exceptional circumstances arise frequently.

#### 14.2.2 Stages of the proposed system

The stages of the proposed production planning system are as follows :-

1. Calculate forecasts for each brand using recent sales details.
2. Adjust these forecasts manually for any special circumstances.
3. Produce the machine loading manually following the handbook provided.
4. Check that the machine loading is feasible.
5. Collect data for product scheduling.
6. Perform the product scheduling on the computer.

#### 14.3 Sales forecasting

Sales forecasts are used by all subsequent modules and obviously the better the forecasts the better these modules perform. In some

circumstances the machine loading decisions depend heavily on the relative reliability of forecasts. The forecasts should therefore give both the expected demand and a measure of its range (see 13.1).

The calculations involved in forecasting from past data are an ideal task for a computer, so computed forecasts should form the basis of this module. Occasionally, outside influences are expected to influence demand, so it is advisable to allow manual adjustments to the forecast. Before computerised forecasting is accepted, it should be compared with manual forecasts. I therefore proposed using three forecasts initially. One would be calculated manually, one on the computer and the major one would be a manually revised computed forecast. The latter forecast should be best; if checks show that it is not, it should be adjusted towards the better forecast by varying the amount of intervention.

#### 14.3.1 Details of the forecasting module

Forecasts are required at all levels of detail and over a wide time-scale. By preparing forecasts at brand level as an annual forecast, all requirements can be met.

Demand by month is found by applying the seasonality; and demand by size by using the sizeroll which remains fairly static through the year. This standard information would need to be stored and revised as appropriate. Demand at higher levels, e.g. by manufacturing group, aggregates individual forecasts.

The computed forecasts would be revised monthly using the formulae given in 13.4. The forecast accuracy is estimated initially, and revised by comparing the forecasts with actual demand.

#### 14.4 Machine loading

The machine loading is prepared manually following the handbook supplied as appendix 4. The basis of this was described in chapter 11. The sales forecasts are an essential input to this module; without reasonable forecasts it is not worthwhile expending much effort on machine loading.

The other information required is a file of basic scheduling costs and parameters for each manufacturing group and details of current stocks and saleable stocks. Combining these details with a knowledge of the current situation, e.g. supply problems, the machine loading is created.

#### 14.5 Product scheduling

There are four stages to product scheduling - data collection, data vetting, calculation of the product schedule and monitoring and adapting the schedule. The data vetting and calculation of the product schedule are performed on the computer.

##### 14.5.1 Data collection

Data necessary for product scheduling includes the demand forecasts supplied by the forecasting module, and the machine loading. In addition one needs to know the sizerolls of each product; the stocks, expected mould loading, etc., at the start of the schedule; various scheduling parameters and special conditions for the current schedule. Separate record types are used for each sort of information.

The sizerolls are obtained from future commitments or information on past sales. The stocks at the start of the schedule are estimated as the current stocks plus production in the intervening period minus demand in that period. The mould loading before the schedule start can also be specified.

The scheduling parameters seldom alter between schedules. They are specified for each manufacturing group and include details like the production rates from each machine, the costs of mould and colour changes, and the weekly limit on mould changes. In addition the number of moulds available for each size must be recorded. Material shortages and some other special circumstances can also be recorded.

#### 14.5.2 Data vetting

Data checking is essential since incorrect data can invalidate the whole schedule for a manufacturing group. For example, too high a sizeroil for one size would force that size to be made early delaying the production of other products.

Two types of check are needed. The data must be valid and complete. A list of likely errors was prepared by the Systems Analyst and myself. These have been coded in two computer programmes. The first checks validity, the second completeness of the data. Since the computer cannot detect all faults, e.g. valid but incorrect data, careful manual checks must also be made.

#### 14.5.3 Calculating the product schedule

Two computer programmes calculate the product schedule. They contain algorithms applying the theory of chapter 9 and cover the many detailed points not described there but necessary in practice.

For example, if one mould is run for half a week another mould must be found for the other half week. Or, if two colours of the same manufacturing group are being made in one week on different machines, the moulds in one machine must be set aside while scheduling the other machine, and then recalled. Data manipulation of this nature occupies

most of the programmes (which are supplied as appendices 7 and 8); the algorithms take relatively little space.

Schedules are determined for one manufacturing group at a time. Runs of 4 weeks or less are called 'short schedules', other runs are 'long schedules'.

The main algorithm in the first programme determines the safety stocks and scheduling requirements. For short schedules the emphasis is on maximising the final saleable stocks. The number of days to produce each colour is chosen to maximise the time before any brand must again be produced.

For long schedules the final safety stocks are assigned to each product in proportion to its demand. Stock projections are then made to see if a uniform production rate will avoid intermediate stockouts. If necessary, the initial production rate is increased or the scheduling interval is divided into shorter periods (see 11.7). The cumulative scheduling requirements by any time are so calculated so give the optimal division between safety stock and freestock (see appendix 4).

Other parts of this programme sort the data ready for scheduling and calculate some basic scheduling parameters. It also provides a useful stock projection informing the management of the likely saleable stock of each brand at the end of each four week period. This should confirm the assumptions made during the machine loading. If a serious discrepancy is observed re-scheduling may be advisable.

The second programme calculates ideal batch quantities for each mould based on the solution to problem A in section 9.3. Scheduling is then performed one week at a time with the priorities calculated as described in section 9.5. The products to mould are selected in

priority order, providing there is still a suitable mould place for them.

A third computer programme of a routine nature prints out the production schedule ready for the planner and others to use (see appendix 9).

#### 14.5.4 Monitoring and adapting the product schedule

Once the product schedule is made, it should be checked to see that it is reasonable. For example, it may be altered to meet any special circumstances not included in the original data. It can then be issued.

Generally the variation between planned and actual output is not large enough to make it worthwhile to alter the schedule. Re-scheduling at 4-6 week intervals will correct such variations. Occasionally a mould breaks down or a large unbalanced order upsets the planned stocks and the schedule should be altered. The principles to observe are to keep closely to the original schedule but to see that once a mould is in, a reasonable batch quantity is made from it. One small change has repercussions through the whole schedule, although individual items generally move only one week forward or backwards.

#### 14.6 Resource planning

Resource planning is part of the preparation of the management plan or its revisions (see chapter 4). It should also be done if the machine loading or product scheduling reveal new information.

New machinery or increased labour forces may be justified when the machine loading projects sustained stockouts from one or more machine



types. Conversely reduced labour forces may be advisable if current stocks are well above the optimal levels.

If stock projections indicate large deficits of one size while using that mould whenever possible, a duplicate mould of that size may be worthwhile. In all these cases, routine planning indicates that something is wrong. Further investigation should show whether to take any action.

#### 14.7 Planned implementation

Implementation was planned to take place in several stages, starting from the final part of the system and working backwards. This order was chosen because (a) the product scheduling seemed to pose the greatest problems as currently performed, (b) it was the least 'political' area to work in, and (c) it would give something which could be used immediately and be seen to be useful. In addition, it was hoped that successful implementation of the product scheduling system would encourage further implementation.

##### 14.7.1 First stage

The first stage in implementation was complete and operating when the form of the production planning system was finally settled. It was a pilot stage designed to show that the proposed scheduling method would work in practice.

The pilot system contained two computer programmes. One performed the mould scheduling (as described in chapter 9), the other printed out the schedule. It had to be run by a skilled technician since data had to be presented in a readily digestible form; in particular, the requirements had to be stated as scheduling requirements.

As explained in chapter 15, I was the only person ever to operate this system, which was replaced by a simpler system in the second stage of implementation.

#### 14.7.2 Second stage

The main object of the second stage of implementation was to consolidate the pilot system into a sound scheduling system which could be run by a trained controller without requiring him to perform extensive calculations. This would release me for work on other areas of production planning and establish the product scheduling module as a continuing system.

A minor objective of the second stage was to present the sales forecasts and machine loading systematically. This would help data preparation for the product scheduling and provide a basis for the third stage of implementation. It was hoped that the more systematic presentation of this information would reveal and remove obvious failings and thus improve the production planning.

##### 14.7.2.1 Details

In this stage, the sales forecasts and machine loading are prepared manually by specific individuals on a regular basis for the product scheduling. The sales forecasts are presented as demand requirements adjusted for any differences in urgency between brands. As stated in 3.6.2 there is no built-in preference for any brand so there is seldom any need to adjust the demand forecasts.

The product scheduling module takes its final form. The main advance is the vetting and processing of the information by the computer so that data can be input in a readily-understood form.

Three new computer programmes are required for vetting and processing, including determination of the scheduling requirements. The original two programmes need some modification with improved algorithms used for the priority calculations. These programmes provide good diagnostic information indicating the likely stocks of each product at any time. This is used to check that the machine loading is reasonable. (It would be unreasonable if there were large stocks of one manufacturing group and projected stockouts of another group, which could be made in its place.)

#### 14.7.3 Third stage

The objective of the third stage is to achieve full implementation of the production planning system. The systematic presentation of information introduced in the second stage makes it possible to implement the third stage piecemeal.

Additional features of this stage are that up-to-date demand forecasts are provided for each brand; secondly the machine loading is determined systematically following the handbook provided.

#### 14.7.4 Timing

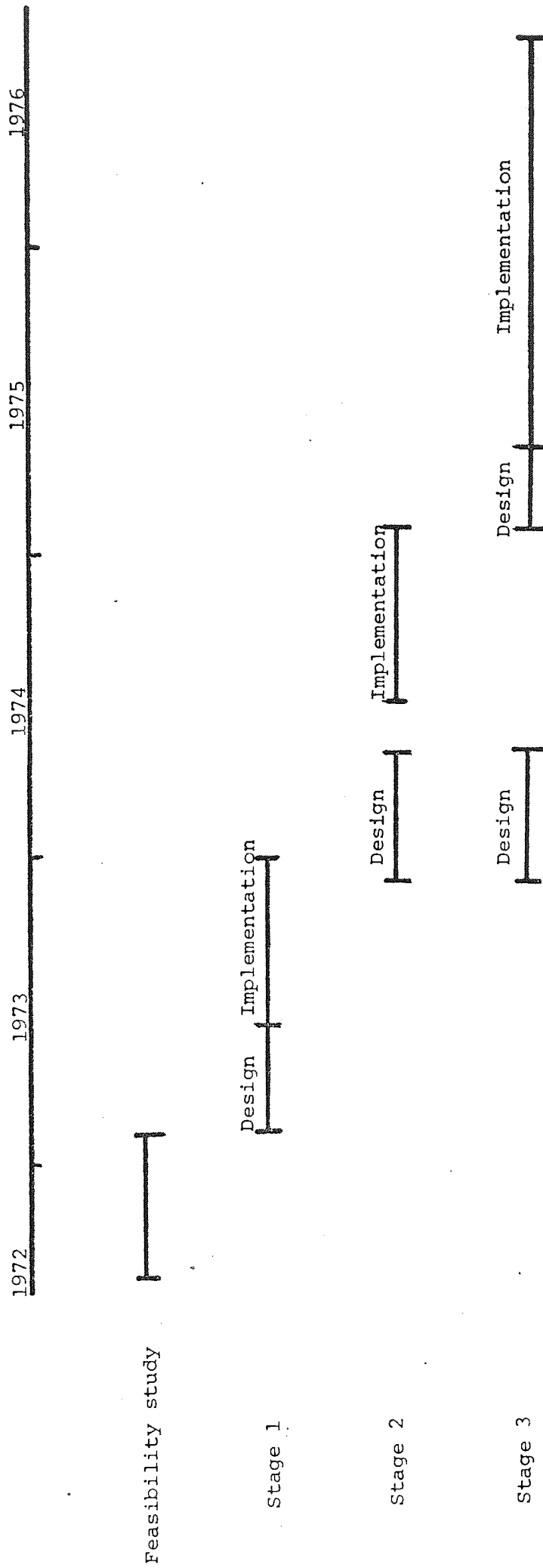
The proposed timing of work on these stages is presented in diagram 36. The main features are that stage 1 should be fully implemented in January 1974, stage 2 in January 1975, and stage 3 during 1976, but with substantial progress by September 1975.

#### 14.8 Later developments

There are three categories of possible developments. These are improvements to the system, extensions of the system and links between this system and others.

Diagram 36

PROPOSED TIMETABLE FOR IMPLEMENTATION



#### 14.8.1 Improvements to the system

Minor improvements and corrections to the system will naturally be made as and when they arise. I do not foresee any major changes. The proposed machine loading algorithms are relatively simple since the quality of information justifies nothing more; with improved data, better algorithms could be used but I doubt this will occur.

#### 14.8.2 Extensions of the system

The system could be extended to the other major production department in the factory. A separate system would be needed since the problems are different, but the current system could be adapted with less than a third of the original effort.

Briefly, the following work would be required. The sales forecasting module could be retained. Machine loading could be dropped since there is nothing comparable to the machine-mould interaction in this department. The scheduling requirements would still need to be calculated. The basis of the priority system could be retained for mould scheduling but a new section would be needed to determine the particular products to make from each mould, and a new programme would be needed to print the schedule. Resource planning would again be separate for the same reasons.

#### 14.8.3 Links between systems

Production planning interacts with many other areas of a company's business so it is natural that the procedures used should also interact. The proposed production planning system will operate independently of other systems; however, I expect it to be linked to them.

At present the only link with other computer systems is that information on current stocks can be obtained directly from stock records. When sales forecasting is introduced the same forecasts can be used in many contexts.

The production schedules are currently issued to the Supplies Executive who uses them to see whether immediate orders can be met. The schedules are also input by hand into another computer system, 'PROMPT', which breaks down the schedule into requirements for each component. These requirements are issued to the Buying Department who order from them.

Likely developments are that Supplies Executive could be given a 'supplies analysis', informing her of the projected stocks if the schedule is kept; permitting closer control over accepting and releasing orders. The schedule could also be directly input into 'PROMPT'.

The production planning system could also be used as a management tool to compare the effects of alternative proposals for the following year. One need only proceed to the machine loading stage to obtain the desired information. It is unlikely that any progress will occur in this area in the next few years.

15.1    Introduction

Early chapters describe the analysis and design of the production planning system. This is of little use to a company unless it is implemented. The problems of implementation, which starts with the decision to go ahead, took a great deal more time than this chapter would imply.

Delays in implementation of stage two prevented full implementation. The delays were outside my and the company's control. I could have produced a more complete theoretical system if I had abandoned any implementation but this would have benefited no-one.

Section 15.2 explains how responsibility for implementation was divided. In particular, the computing was shared between myself and the computing department. Section 15.3 describes my initial work briefly and explains why implementation started with the mould scheduling module. Sections 15.3 to 15.6 describe the stages of implementation and should be read in conjunction with the corresponding sections in chapter 14.

The actual performance is presented and analysed in section 15.7 which concludes that the actual implementation has been successful.

15.2    Responsibility for implementation

The analysis and design work on this project was entirely my responsibility. Company staff, most helpfully, provided all information requested but, with advice from my supervisors, I processed and interpreted it.

Implementation, which starts with the decision to implement, cannot be entirely my responsibility if the project is to be successful. The Company must make the decisions and run the eventual system.

#### 15.2.1 Manual procedures

I agreed to train people to perform the manual procedures providing the company would assign staff to these tasks so that they could take over the running the system.

#### 15.2.2 Computer procedures

Implementation of a computer system includes the writing and testing of computer programmes. The company agreed to write the necessary input and output programmes which would be typical of business programmes. I agreed to write the scientific programmes encoding the logic of my algorithms. The systems Analyst and I shared the responsibility for specifying and testing the other programmes.

We checked that mixed programming was feasible and decided to write the scientific programmes in Fortran, a scientific language and business programmes in Cobol, the Company's standard language. (This makes it harder for company staff to amend the scientific programmes, but easier for another Operational Researcher to do so.)

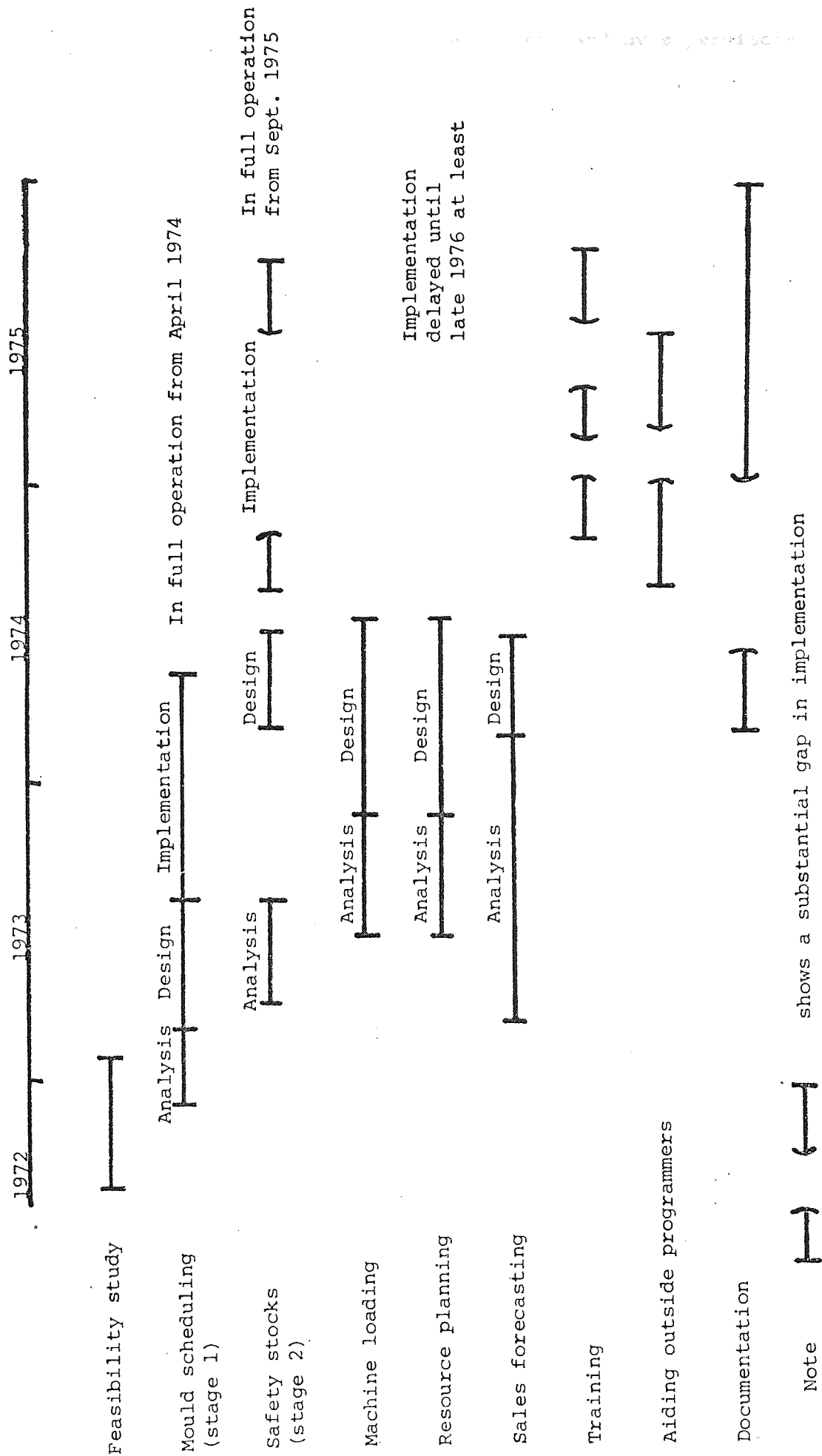
#### 15.3 The initial work

I spent the first three months working with others on their jobs. I started on the shop floor, visiting each relevant department, and then worked with the planner, planning manager and market researcher. During this period I became familiar with the company's operations concerning this project.



Diagram 37

TIMETABLE FOR ACTUAL IMPLEMENTATION



I then produced a feasibility study for the project, which is summarised in chapter 4. As a result of this, Dunlop Management and my supervisors agreed that the project should proceed.

It was thought desirable to obtain some early results, so rather than proceeding uniformly we decided to concentrate on the mould scheduling module. The approximate subdivision of the project was evident at this stage (see 5.2). Mould scheduling would clearly be part of any system. Its requirements would be similar to the requirements of the existing system, so this decision should not prevent an optimal design. Other advantages of this decision were stated in section 14.7.

#### 15.4 Implementation Stage 1 - The pilot scheme - Mould scheduling alone

Once a satisfactory system for mould scheduling had been designed, as described in chapter 9, and shown on a simple example to improve current practice, I discussed implementation with the planning manager and systems analyst.

We proposed that the initial system should be simple to minimise the loss if it failed. I therefore agreed to operate the system initially and to perform a lot of the data preparation which the computer would eventually do. Two computer programmes were required, one to calculate the schedule, the other to print it out.

I wrote the scheduling programme and the Company contracted out the print programme. After some simple tests and comparison with a real schedule I was satisfied with the results for the major manufacturing groups. Schedules for short periods, or where the size range should be restricted but only one machine was available, were poor.

I suggested partial implementation for the acceptable groups and

produced a mould schedule. The planner examined this and subsequent schedules critically; he suggested some improvements but accepted the schedule and issued it.

During the next six months I improved the programme. Short schedules were improved by looking forward to the schedule finish, and the size ranges restricted by including a penalty cost for running a wide range of sizes. Several other minor problems were ironed out.

Four more schedules were issued in these six months. They demonstrated that mould scheduling could be done effectively by computer. The unbalanced stocks were substantially reduced for similar production costs (see diagram 16 earlier).

Preparation of the data took two or three days per schedule and required a mathematician for some of the calculations. The scheduling programme frequently failed and had to be re-run because of errors in the data. I therefore suggested further implementation should occur.

## 15.5 Implementation Stage 2 - The complete product scheduling module

### 15.5.1 Proposal

In April 1974 I organised a presentation for all concerned with the project from the planner to the General Manager. I described current progress and explained how the pilot system had enabled substantial extra sales to be made.

The pilot system could only be run by a skilled technician so I suggested that additional computer programmes be written to enable the work to be done by a trained controller (see 14.5 and 14.7.3). I would then be freed from routine running of this system and would be

able to finish the design of the remaining modules and to start to implement them (stage 3 of implementation).

These proposals were subsequently accepted. Staff were assigned to perform the necessary tasks and I agreed to train them. The programming was to be done as soon as possible; since the company had no free programmers, the work was contracted out. The programmes should have been completed by September and the training finished in December so that the system could run live in January 1975.

#### 15.5.2 Programming

Three new computer programmes were required; one to check the validity of the data, one to check completeness and one to calculate the scheduling requirements. I wrote the latter programme and helped to specify the other two programmes. I also produced extensive test data.

Unfortunately, the firm chosen to write the Cobol programmes was incompetent. A series of programmers had to be taught all about the problem, made some progress, then left, saying it was nearly finished when hundreds of errors still remained. Eventually they abandoned the job in November.

A second firm took over their programmes in February, abandoned and rewrote one, and finished in May 1975. The programmes were then tested and corrected in June and July. Comparison with a schedule from the pilot scheme demonstrated that the new system was better than the pilot scheme and it was therefore implemented in August 1975.

#### 15.5.3 Training

Four people are needed to operate stage two of the system. Three

prepare data for the scheduling system and one controls this system. The planning manager, who decides the machine loading, and the planner needed little training to prepare their data.

The supplies executive presents the demand requirements to the scheduling system. These reflect the priorities of individual customers. It was necessary to explain carefully how these priorities are included in the requirements. The main problem here has been the irregular receipt of this information.

The controller needed substantial training on collecting the information, writing it out, and overseeing the operation of the system. He was nearly trained by the end of November and, had the programmes been ready, the system would have been implemented on time. (A controller's manual intended as an aid is supplied as appendix 3.) Without practice, the controller needed retraining twice before the 'almost complete' programmes were completed.

#### 15.5.4 After implementation

The new system ran live from August 1975 with no more than the expected teething problems. Instead of the minimum of six months bedding in, only six weeks were left before I would have to complete the project, so major but soluble problems may arise later although none have arisen yet (May 1976). This delay means that the performance of the scheduling system cannot be measured and all results must be based on the pilot system's schedules.

To assist continuing implementation, manuals, advice and examples have been provided for those involved in running, maintaining or using the system. These will help new staff to take over the job as existing staff are promoted or retire.

## 15.6 Implementation Stage 3 - The full production planning system

Work on stage three was planned to start in January 1975 so that by September some parts would have been implemented, and the remaining implementation would be straightforward.

I could not overlap work on stage three with stage two since my time was fully occupied in operating the pilot system, training the controller, overseeing the outside programmers and documenting my work.

By the time stage two was complete there was insufficient time for reasonable progress on stage three. It must therefore await a suitable opportunity, and the company plans further progress for late 1976.

The only completed parts of this stage are a handbook on determining the machine loading (appendix 4) and suggested formulae for use in sales forecasting (see 13.4.3).

One future development to link the schedules with the 'PROMPT' system (see 14.8) is currently in progress. Other developments are again planned for late 1976.

## 15.7 Performance achieved

### 15.7.1 Introduction

Since the stage 2 system has only been running for a very short time, most of the performance measures given here relate to the stage 1 system. The stage 2 system is theoretically better and performed better in comparative tests, so these performances should at least be equalled.

With no stage 3 implementation many of the performance tests are not appropriate. Nothing has happened on sales forecasting so the

performance there should be static. The machine loading is now done more systematically and a slight improvement is expected.

Since full implementation of stage 1, the demand for footwear has continually been high and the stocks low. Sales forecasting has therefore presented no real problem, since known orders exceed immediate capacity. The machine loading has also needed to consider only immediate demand and so the present (manual) system has performed well. Only the product scheduling has been seriously tested, needing to operate on minimum freestocks. The situation has therefore been untypical.

#### 15.7.2 Separation of class one and class two manufacturing groups

The proposed planning system differs for class one and class two manufacturing groups. It is inappropriate to use the same measures in each case.

For example, one has direct control through the machine loading of stocks of class two groups which form a small part of the total stock. However the overall production rate is pre-determined, so there is negligible control over class one stocks. The performance measures are therefore given separately for class one and class two manufacturing groups.

#### 15.7.3 Measures of performance - class one groups

The measures of performance here compare actual performance with the optimal performance expected from the model introduced in chapter 11 (see also 4.4). It is not generally valid to compare directly costs on different occasions, since the optimal costs depend greatly on the net stock which is determined by factors outside the planning system. Comparisons are therefore made for a given stock

level.

The expected costs can vary from near zero to very large; a moderate difference between optimal and actual costs is more significant in the former case. The performance measures therefore indicate the proportional shortfall from the optimum cost.

#### 15.7.3.1 The model (see chapter 11)

For any given net stock, the costs can be divided into storage costs, which are virtually fixed, shortage costs related to the planned balanced stock, and production costs related to the planned freestock.

#### 15.7.3.2 Measure of overall excess costs

The excess overall cost measure is the excess of actual costs over optimal costs for that stock expressed as a percentage of the actual cost. This shows the combined effects of the machine loading and product scheduling modules.

#### 15.7.3.3 Effective use of freestock

The measure of the effectiveness of freestock is the excess of production costs over optimal costs for that freestock expressed as a percentage of the actual cost. This indicates the effect of the mould scheduling module.

#### 15.7.3.4 Effective use of balanced stock

The measure of excess shortage costs is the excess of shortage costs over their optimal value for that balanced stock expressed as a percentage of the actual cost. While the machine loading influences this result, its main use is to show the effectiveness of the safety stock module.



#### 15.7.3.5 Optimal splitting of the stock

The measure of the optimality of the stock split is the difference between actual and optimal freestock expressed as a percentage of the actual freestock. This shows how well the machine loading module has split the stock into its component parts.

#### 15.7.3.6 Notes on these measures

The ideal measure is 0 which indicates that actual cost equals the optimal cost. The target level for most measures is 25% (see 4.5). Since the optimal cost relates to the expected value not the value on a specific occasion, the actual cost may be below the optimum. In such cases, which indicate unusual circumstances combined with good use of resources, the performance measure is negative.

To avoid enormous measures, the excess cost is expressed as a percentage of the actual cost (not the optimal cost). The worst result is a measure of 100 which indicates that the optimal cost is below  $\frac{1}{2}\%$  of the actual cost.

No sales forecasting measures are included here since no implementation has occurred in this module.

#### 15.7.4 Results for class one groups

The performance was measured on five random dates, A to E, between January 1973 and June 1975 (see 10.5). The original planning system was in use on the first two dates, A and B; the new scheduling system was in operation for the last three dates.

The results are presented by machine type and include all class one groups of that type. No results are given for the medium protective

machine which was acquired recently.

The results are summarised by giving average performance measures before and after implementation. These are calculated from the actual total cost and optimal total cost for each machine type, and then averaged over the machine types.

#### 15.7.4.1 General comments on the results (Details in tables 22 to 25)

The overall measure of excess cost (see table 22) has fallen from 54 before implementation to 24 after, with good improvements for each machine type. This improvement is analysed below.

A startling improvement has occurred in the effective use of free-stock. The wasted production freestock has been reduced from 72% to 19% (see table 23). Thus, before implementation, the freestock used was  $3\frac{1}{2}$  ( $=100/(100-72)$ ) times that necessary, whereas it is now below the target level of 25% (see 4.5). It is reasonable to attribute this to the scheduling algorithm which avoids excess freestocks and makes optimal use of the planned freestocks.

The shortage costs have also been greatly reduced with the wastage measure reduced from 83 to 29 (see table 24). This results from the more frequent scheduling under the new system, good machine loading, and from the safety stock policy. It is an unexpected result, since the safety stock policy is simple, but shows the advantages of having a policy. The expected savings here exceed the target of £2,500 set in section 4.5.

The split of stock between freestock and balanced stock was fairly good before implementation so the potential improvement was limited.

It has actually improved from 26 to 11 (see table 25). Since sales variations affect this measure, the current performance here is good.

#### 15.7.4.2 Validity of the results

No major changes have occurred between 1973 and 1975, except that stocks were generally high at dates A and B and low from C to E. If the model underestimated the costs for high stocks, misleading results could occur. It is shown below that this is unlikely. Firstly, for the large protective machines, dates B and C are directly comparable (same net stocks). The improvement from B to C in each measure is very similar to the overall improvement.

Secondly, the production plus shortage costs (i.e. excluding storage costs) should decrease as stocks increase. Yet, for each machine type, the production plus storage costs on one date before implementation exceed these costs on two subsequent dates despite significantly higher stocks in the former case.

These results uphold the validity of the model and show that improvements from implementation are real.

Note that storage costs, which are fixed, are included in the overall cost measure so reduce the improvement shown in this measure.

#### 15.7.4.3 Summary of results for class one groups

The overall results are most encouraging. For each machine type and each measure - on overall costs or an aspect of these costs - the improvement after implementation is at least as good as that expected in the feasibility study (see 4.5). In particular, the excess overall cost measure has come down from 54% to 24%.

Table 22

Measure of overall excess costs

Percentage of total cost which was avoidable

Date	Machine Type			Mean
	Small Protective	Large Protective	Canvas	
A	41	42	55	
B	67	73	19	
Average before implementation	56	62	43	54
C	0	19	11	
D	43	23	39	
E	18	6	23	
Average after implementation	31	20	20	24

Table 23

Effectiveness of freestock in controlling production costs

Date	Machine Type			Mean
	Small Protective	Large Protective	Canvas	
A	70	80	66	
B	80	68	70	
Average before implementation	75	74	68	72
C	42	5	10	
D	36	24	36	
E	-161*	32	47	
Average after implementation	5	24	29	19

\* Negative values indicate better than optimal performance due to exceptional circumstances

Table 24

Effectiveness of planned balanced stock in reducing shortages

Date	Machine Type			Mean
	Small Protective	Large Protective	Canvas	
A	100	97	100	
B	56	79	89	
Average before implementation	69	83	98	83
C	-51*	4	48	
D	35	20	67	
E	75	3	-67*	
Average after implementation	33	17	36	29

\* Negative values indicate better than optimal expected performance due to exceptional circumstances

Table 25

Effectiveness of splitting stock between freestock  
and balanced stock

Date	Machine Type			Mean
	Small Protective	Large Protective	Canvas	
A	22	4	9	
B	59	34	29	
Average before implementation	40	19	19	26
C	8	27	1	
D	11	3	9	
E	12	1	27	
Average after implementation	10	10	12	11

#### 15.7.5 Measures for class two groups

For class two groups the current position depends on the time since the last production run. Measures taken on one day are unreliable, so costs should be examined over a full production cycle. The marginal value of stock should be taken as that appropriate for the class one groups of the same machine type.

With this proviso, all the class one measures - on overall cost, production cost, shortage cost and split of stock - can be used. In addition one can measure the difference in the batch quantity from its optimum as a proportion of the optimum, and the difference in weeks between the actual starting date of production and the ideal date.

In all cases the ideal measure is zero, and as performance worsens the measure increases.

#### 15.7.6 Results for class two groups

The class two groups have been continually affected by shortages or excesses of stocks so details of several measures are meaningless. In another case the optimal performance is always achieved so only one table (no. 26) is provided, showing how well the freestock is kept down while out of production.

Prolonged shortages of raw materials at some times, coupled with overproduction at other times due to excess stocks, render accurate measures of overall and shortage costs pointless.

The part of machine loading dealing with the timing of machine changes was not implemented in this period so no improvement appears



Table 26

Measure of excess freestock while out of production  
for class two groups

Date	Machine Type	
	Small Protective	Large Protective
A	78	-
B	(316) *	(353) *
Mean before implementation	197	(353) *
C	61	11
D	22	78
E	0	2
Mean after implementation	28	30

Notes: \* At time B the small protective run was cut short, and technical problems appeared on the large protective run.

No reliable figures are available for the canvas machines.

with the timing which is generally 4 weeks out.

Significant improvements in the above three measures should appear if an effective machine loading system is introduced.

All batches of class two groups between 1973 and 1975 have been of the minimum reasonable length with no unnecessary mould changes. Initially the products were new, justifying short runs, and recently the marginal value of stock has been high, thus the performance here has been optimal. As stocks rise, batch sizes should slowly increase.

As table 26 shows, the excess freestocks after production are now 30% above optimum. This is well below the initial levels; these were however affected by production problems and the recent introduction of these products. Nevertheless the improvement is encouraging.

#### 15.7.7 Conclusions

Introduction of the product scheduling system has significantly reduced the costs for class one manufacturing groups, with good improvements in all areas. The effect on class two groups has been small but useful.

The continuing high demand has fully tested the product scheduling but has not stressed the machine loading or sales forecasting which have performed well in their original forms. Earlier evidence suggests their performance can be significantly improved in normal conditions.

The company is now operating satisfactorily on stocks which, at a time of high demand, are 200,000 pairs below their former level. Better scheduling has certainly contributed at least half this

reduction. The company has therefore sold at least an extra 100,000 pairs as a result of this project and can now operate on significantly lower stock levels. With only partial implementation, the project has achieved its target set in the feasibility study (see 4.5).

In conclusion, the scheduling system has been a success and should continue in operation. Implementation of the machine loading (and forecasting) modules will enable these savings to be retained when demand falls to more normal levels.

16.1 Introduction

The production planning system proposed in this thesis is custom-designed for a specific factory making injection-moulded footwear. It is not therefore intended to be widely applicable.

Where the system resembles standard proposals it provides nothing new to apply elsewhere, so in section 16.2, the solutions are compared with standard proposals in the literature. The structure is only unusual because the problem and its environment force some changes. The scheduling solutions are unusual, but not the sales forecasting or resource planning.

Section 16.3 then discusses wider applications of this system. It concludes that there are potential applications in heavy engineering, the car industry and seasonal industries. The mould scheduling solution is the most likely to be applied elsewhere, either for other injection moulding machines or at Dunlop Footwear for compression moulded products.

16.2 Comparison with the literature16.2.1 The structure of production planning systems

A 'standard' production planning system, e.g. (14), has a 'forecasting module', an aggregate 'resource planning' module, and a detailed 'scheduling module'.

The proposed production planning system is similar. Differences are imposed by the structure of the problem, which is well constrained. Resource plans are made outside the system, with advice from the

production planners, so resources are essentially fixed; with seasonal demand, stocks are rarely near their ideal level.

An unusual feature, necessitated by the machinery, is that scheduling occurs at two levels instead of one, inserting an extra stage in the system. The resulting structure is a natural modification of the standard (see diagram 35 and 5.2).

#### 16.2.2 The forecasting module

The forecasting module is similar to many proposed in the literature. It uses a forecasting technique appropriate to the particular seasonal context, otherwise there is nothing unusual about it.

#### 16.2.3 The resource planning module

Resource planning is a minor part of this production planning system; the suggestions are specific to this problem but the thinking is unexceptional. It manipulates models of the system to see the effects of a change in resources.

#### 16.2.4 The machine loading module

The machine loading module is unusual; it resembles both resource planning, because it aggregates the scheduling results, and detailed scheduling, because the machine loading is itself a schedule.

The aggregation is specific to this problem with its classification into class one and class two manufacturing groups. The principle is however standard, see e.g. Holt et al. (33) who aggregate the cost of constrained batch quantities.

Little work has been done on scheduling with seasonal stochastic demand (see the literature review in chapter 11). Dynamic

programming would give an optimal solution, but is impractical; other standard approaches cannot solve the problem. The proposals in chapter 11 leave much to be done in this area.

#### 16.2.5 The product scheduling module

The unusual feature of the product scheduling module is the use of a priority system to schedule variable size batches, particularly since the priority can consider many external factors.

Constrained economic batch quantities which form the basis of the system, are common in the literature, but have seldom been adapted to a scheduling problem. Cox and Jessop (32) provide a similar approach.

The treatment of safety stocks is unusual; it is uncommon to vary them continually throughout the year to cope with seasonal and short-term variations in stock. However the result that safety stocks should be proportional to sales, not their square root, occurs elsewhere (e.g. (72)).

### 16.3 Generalisability

#### 16.3.1 The structure

The precise structure of this system will not apply to many other companies, but parts may. Constrained production planning is probably more common in practice than in the literature with many companies giving their planning department little scope to meet fluctuations in demand.

Heavy engineering companies are amongst those used to fluctuating order books. Where some components are batch produced on machinery

with little spare capacity one has a similar problem to this one.

If in addition the machinery can have major and minor set-ups the semblance becomes much stronger. One might then have two stages in scheduling.

Multi-station injection moulding machines are used by several other footwear companies to which this system would be almost directly transferable. They are also used by plastics manufacturers making parts for the car industry; the proposed production planning system might also be relevant here.

#### 16.3.2 Machine loading

The machine loading involves scheduling to meet seasonal demand where the information improves throughout the season. It is only relevant to seasonal industries such as sports goods, greetings cards or seasonal clothing. In most of these cases production commences well before the season, but there is time for late corrections.

There are rarely major set-up costs so production proceeds uniformly for each product. Where set-ups occur, as in printing greetings cards, only one print-run is normally made and re-runs are exceptional. The full problem only arises if several set-ups are needed for each product each year.

For this reason the machine loading solution is unlikely to be appropriate except for injection-moulding machinery. Production planning in several of these other industries is discussed in the literature, e.g. (41), with strong emphasis on the need for reliable forecasts, but a common approach has yet to be adopted.

### 16.3.3 Mould scheduling

The principles of the mould scheduling solution - to approximate an ideal solution using Economic Batch Quantities - are applicable in a batch manufacturing environment with little or no spare capacity and several identical machines available for processing.

With only one machine, interactions between products become severe and a fixed cycle for each product may be more appropriate. With plenty of spare capacity, batches need not be started early; instead the machines lie idle and Cox and Jessop's solution is appropriate.

The priority system however involves more than this since it can consider raw materials shortages or additional production costs. It may be possible to adjust other planning methods to take account of additional costs by converting them to a priority basis.

The full system is applicable to other factories making injection moulded products on multi-station machines. Note finally that the system can be converted for rubber compression-moulded footwear also made at the Dunlop factory (see 14.8.2).



### 17.1 General conclusions

The project is a qualified success. It has studied the whole production planning system and achieved its main objective, the implementation of a 'product scheduling' system, but no further implementation has occurred.

The production planning system was divided into four sub-systems - sales forecasting, resource planning, machine loading (scheduling at an aggregate level) and product scheduling (scheduling at a detailed level).

All four sub-systems have been studied and modelled. The models are specifically designed for the problem environment, so should be more suitable than alternative proposals. Results from each model compare favourably with current practice, thus validating the models. Further details on each sub-system are presented in 17.2.

The production planning system has been designed on a modular basis with one module for each sub-system. The modules can be run separately but are designed to operate together. They should perform better jointly than individually.

My approach seeks good feasible solutions rather than 'better' but 'infeasible' solutions. It is justified by the good results obtained on product scheduling (see 17.3).

The specific success of this project has been the 'product scheduling' module which performs near to its theoretical optimum and has been implemented in some form for over two years. The minor failing has been the lack of further implementation, particularly in machine loading.

Reasons for these successes and failings are discussed in section 17.4.

## 17.2 Details of the sub-systems

### 17.2.1 Sales forecasting

The object of sales forecasting is to produce objective sales forecasts of high accuracy.

#### 17.2.1.1 Conclusions of the analyses

The annual demand for most brands is well forecast by a simple technique known as exponential smoothing. Such forecasts are generally better than those made by more complex methods.

Monthly demand has a regular seasonality with the proportion of annual demand occurring in each specific month remaining roughly constant. Out of season the basic demand is low and random variation is proportionately greater. The recommended forecasting method therefore takes less account of the out-of-season demand and more of the in-season demand. More common methods give equal weight to all months but give poorer forecasts in this instance.

Mud and slush increase the sales of protective footwear. The ground conditions are estimated by a 'slush' index which correlates well with sales of protectives. Most of the resulting demand occurs nine months later when wholesalers and retailers restock, so this result is useful for forecasting short and medium-term demand.

#### 17.2.1.2 Proposal

The proposed forecasting system combines subjective manual forecasts with the objective computed forecasts. Had this been operating from 1972 the forecast errors would have been significantly reduced.

No immediate implementation is likely but a further study is due in 1976 when it is hoped that these proposals may be implemented.

#### 17.2.2 Resource planning

The major resource planning decisions are made by the management committee after considering many aspects of the problem. The resource planning module should calculate the financial benefits of new investment in machinery and moulds, and the effect of an adjustment to the labour force.

##### 17.2.2.1 Proposals

New machinery can reduce storage, shortage and production costs. The potential benefits can be calculated by manipulating the 'machine loading' model. The purchase is worthwhile if the expected gain exceeds the depreciation and running costs.

Additional moulds are only worthwhile as a method of restocking quickly after a shortage. A duplicate mould is desirable if demand reaches 95% of production capacity.

Changes in the labour force will affect future stock levels and alter the storage and shortage costs. These can be calculated from the 'machine loading' model. Before making any decisions management should also consider the effect on morale, etc.

##### 17.2.2.2 Validity of these proposals

By following these proposals all actual decisions would have been made. In addition one further mould would have been purchased to the benefit of the company.

#### 17.2.2.3 Implementation

No immediate changes in the resources are likely. These suggestions may be followed when making future decisions, but it will be a long time before they are fully accepted.

#### 17.2.3 Machine loading

The machine loading module determines the manufacturing groups to load into each machine in each week to minimise the expected scheduling costs for a given set of resources.

##### 17.2.3.1 Analysis

This problem involves the scheduling of batch production for products with an unknown seasonal demand. Its complexity rules out standard approaches but it is reasonable to consider only one class of basic solutions.

The costs are aggregates of the product scheduling costs. Reasonable estimates of these can be obtained and the future costs can thus be evaluated.

##### 17.2.3.2 Proposals

Since a wide variety of constraints make computerised scheduling infeasible, the costs must be determined manually. A simplified procedure which approximates the above solution is proposed (see appendix 4).

Qualitative comparisons with current practice show that these proposals would produce acceptable mould loadings with low savings in times of high demand, but good savings at other times.

#### 17.2.3.3 Implementation

With the present order backlog, machine loading is not difficult and implementation of these proposals is unlikely. Once circumstances alter the company may be willing to implement a machine loading system which could save several thousand pounds a year.

These proposals should form a starting point for future work which might implement them directly or might involve further academic study.

#### 17.2.4 Product scheduling

The product scheduling problem is to schedule the colours, moulds and products to be made on each machine in each week of the scheduling interval to minimise the production and shortage costs, subject to a given machine loading and given production rate.

##### 17.2.4.1 Analysis

The company is a batch manufacturer with unusual additional production costs related to the group of moulds running together in a machine. These costs were estimated from a detailed analysis of output statistics.

Constraints on the production rate fix the expected stocks at any time so the ideal batch quantities and safety stocks cannot be used. However, given the total safety stock and the total 'freestock' for batch production, standard theories enable one to determine ideal batch quantities and safety stocks.

##### 17.2.4.2 Proposal

The optimal split of stocks between safety stocks and 'freestock' is determined by considering aggregate costs. The total safety stock

is then divided between the brands and sizes; these safety stocks are added to the cumulative demand for each item to give the 'scheduling requirements' for each item.

Optimal batch quantities for each mould using the available 'freestock' for batch production are calculated. Scheduling proceeds on a weekly basis aiming to produce the optimal batch quantities and to meet the scheduling requirements. Each product is given a priority which reflects the expected gain or loss from production of that product; products are scheduled in order of priority providing that they can be allocated a suitable mould place.

#### 17.2.4.3 Validity of model

This model was first tested on a simple theoretical problem where it proved better than all manual schedules and nearly optimal. It has since operated in practice with manual determination of safety stocks for over two years. The production costs for a given free-stock keep near their minimum possible value and are well below their earlier values.

#### 17.2.4.4 Implementation

This module was implemented into two stages. The first stage was a pilot stage including only the mould scheduling. The safety stocks were determined manually following an appropriate algorithm. The second stage, which was implemented in August 1975, includes the full product scheduling module and incorporates the above algorithm to set the safety stocks.

### 17.3 Validity of the approach

The main feature of the approach, as stressed in chapter 6, is to ensure

that proposed solutions are feasible or can easily be made feasible. This has led to the use of progressive solutions which are determined one period at a time, rather than complete solutions determined as a whole. The latter approach can give a better solution to the model but the former approach is readily adaptable to the outside environment.

Where, as with this project, circumstances are continually altering and it is difficult to adjust a proposed but infeasible solution to a good feasible solution, progressive solution techniques appear best. They certainly give good feasible solutions in this instance, particularly with the product scheduling module.

#### 17.4 Successes and failings of the project

The terms of reference for this project (see also 1.9) were, briefly:-

- A. To design a production scheduling system for the Injection Moulding Dept. and to implement it if accepted by management.
- B. To determine the effects of further capital investment in machinery and moulds.
- C. To investigate sales forecasting.

The work on product scheduling and machine loading concerns part A; the resource planning part B; and the sales forecasting part C. The terms of reference have been fully met except for the failure to implement any machine loading proposals due to lack of time.

Since product scheduling was, and still is, Dunlop Footwear's major concern, the project has been a success from their viewpoint. The product scheduling module now seems firmly established. It is unfortunate that the machine loading has not yet been implemented. Implementation in other areas was not expected by the Company; any

benefits from these areas will enhance the success of the project, but are not essential.

#### 17.4.1 The main failure - Lack of implementation on 'machine loading'

The project's main failing is the lack of implementation on 'machine loading' due to lack of time. The completed design is contained in the handbook issued as appendix 4. This would have been polished up during implementation.

Once the pilot stage was operating successfully, it was apparent that implementation would be a problem since the company saw no urgency in taking over the system while I was running it.

The systems analyst and I stressed the desirability of full and early implementation of the whole product scheduling module. I would then be free to concentrate on the remaining problem areas and there would be plenty of time to resolve the teething troubles of the product scheduling module.

Belatedly the company agreed to our proposals. All might have been well had the outside programming been done by a competent company. Unfortunately it was not, and prolonged delays occurred. As a result the 'machine loading' could not be implemented.

The project was expanded beyond product scheduling at the University's request (see 1.9) without any strong commitment from the company in these areas; the lack of further implementation, while disappointing, reflects in part the company's desires.

Possible lessons to the researcher from this are that, if you provide what is most wanted first, you may not get the chance to provide the rest later; also, before taking over a job while implementing it, ensure that you will shortly be relieved of this responsibility.



#### 17.4.2 The main success - Product scheduling

The product scheduling module is particularly successful because it operates near to its theoretical optimum and because it was implemented during a period of high demand when it was immediately of great benefit.

The first feature is part of the design and shows that progressive solutions can be nearly optimal. It confirms that my approach is justified.

The second feature is pure chance and very fortunate. The company has saved many thousands of pounds in storage costs by using the module. It has also sold more footwear than would otherwise have been possible. Had demand been low the company would have gained little from this module and better resource planning or machine loading would have been more appropriate. As it is, the reduction in stocks can be permanently maintained giving an annual saving near the target for the whole production planning system.

#### 17.5 Summary

Overall the project is a success. A full production planning system for the Injection Moulding Department has been designed and partly implemented. The part which has been implemented has run successfully for over two years. By a fortuitous combination of circumstances it has saved several times its annual target through permitting the company to make extra sales. Intelligent planning in the future will retain the stock saving achieved.

The remaining parts of the system should be implemented in the future, possibly by another researcher. These parts yield their greatest

benefit when demand is at a more normal level and the decisions taken in the off-season depend on unknown future demand. The benefits from the full system should comfortably exceed the original target of £8,000 per year.

## GLOSSARY

<u>Term</u>	<u>Reference Section</u>	<u>Brief Description</u>
Balanced stock	2.2.1	Stock that can be sold before any size runs out
Best	2.5.4	Top quality output
Boot	2.3	All plastic footwear such as wellingtons
Brand	Table 2	All sizes in a particular colour and style of footwear
Canvas shoe	2.3	Footwear with a canvas 'upper' and plastic sole
Class one manufacturing group	7.6.1.4	A manufacturing group (q.v.) in almost continual production
Class two manufacturing group	7.6.1.4	A manufacturing group (q.v.) only occasionally in production
Closing room	2.5.2	The department where 'uppers' are closed (sewn up)
Colour	2.4.4	The injection colour or colours of the plastic
Colour change	2.4.6	Changing the injection colour
Colour freestock	9.5.5	The part of the total freestock (q.v.) which permits batch production of each colour
Compatible (of moulds)	2.4.4	Moulds which can be in production together
Concave costs	11.4.2.2	Cost curves for which the marginal cost is non-increasing
Convex costs	7.2	Cost curves for which the marginal cost is non-decreasing (U-shaped)

Critical size	2.2.1	The size which will first run out of stock if there is no further production
Cycle time	8.4	The time taken for an injection-moulding machine to index one station
Die	2.4.2	An individual metal part of a mould
Downtime	8.4	The ineffective production time, i.e. time during which the machine is not producing for mechanical, electrical and other reasons
Dynamic Programming	9.2.2	A recursive technique for finding the optimum solution after first finding the best solution in the final period
Economic Batch Quantity	7.2.2	The optimum quantity to produce in each batch under certain well defined conditions
Essential size	10.3.1	A size whose absence from a delivery will cause the customer to reject the order
Expected discounted profit	3.2.1	The expected total profit when profits in future periods are discounted at a fixed rate of interest (typically 10-15%)
Exponential smoothing	13.3.1	A forecasting method. The forecast is a weighted mean of the previous forecast and previous demand

Finishing	2.5.4	Checking, trimming and packing a boot or shoe
Fitter	-	An engineer who adjusts and maintains the machinery
Flushing the barrel	2.4.6	Changing the colour in the injection barrel to a darker colour
Footwear	-	Generally refers to plastic footwear here - either shoes or boots (q.v.)
Freestock	5.5	The planned level of freestock - used to reduce production costs
Heuristics	11.4	Principles used in decision making when all possibilities cannot be fully explored
Horizon Planning	11.4.2.2	A solution approach which identifies natural planning horizons
Injection barrel	2.4.1	Where the plastic is melted and mixed
Injection moulding	1.6	Production by injection of a plastic into a mould
Injection screw	2.4.1	Internal part of the injection barrel
Lagrangian multiplier	7.4.1	Use of an implicit cost rather than a true cost to control a solution
Last	1.6	The central, leg-shaped part of a mould

Linear Programming (L.P.)	9.2.1	Mathematical technique appropriate when all constraints, etc., are linear
Lining	2.5.1	Interior lining to a boot. Also includes the term 'upper' (q.v.)
List number	Table 2	Unique identification for each brand
Machine loading	2.6.3	Determination of an aggregate schedule
Machine type	2.4.3	Identifies the class and size of a machine, e.g. large, protective
Management plan	4.2	A company policy document planning the next year in detail
Manufacturing group	2.4.4	A set of products, or brands, using compatible moulds
Moulds	2.4.2	The two sets of moulds needed to make a pair of footwear (Template is used to refer to only one set of moulds)
Mould change	2.4.5	Replacement of one 'mould' by another
Moulding	2.4	The output from a mould
Mould-place	2.4.2	A pair of stations on a machine which will hold a 'mould'
Mould schedule	5.7.1	A schedule stating which moulds to use in each machine each week
Mould scheduling	5.7.3.2	Calculating optimal batch quantities and hence the mould and product schedules

Near optimal (of a solution)	6.3	A nearly optimal solution and often the best that will be found in practice
Net production rate	8.4	The production rate after allowing for an average rate of downtime
Normal distribution	10.2	A standard statistical distribution
Opportunity costs	7.6.2.2	Costs arising because current decisions restrict the range of possible future decisions
Optimal	6.2	Best. Often refers to the solution of a model not the true problem
Polyvinylchloride	1.3	A plastic much used in the footwear industry for injection moulding
Product	Table 2	A specific size of a specific brand
Production budget	4.2.2	Part of the Management Plan (q.v.) dealing with production
Production planning	2.6	See supplement on planning terms
Production scheduling	2.6	See supplement on planning terms
Product schedule	5.7.1	A schedule stating which products to make from each machine each week
Product scheduling	2.6.3.2	See supplement on planning terms
Protective boot	2.3	Rainproof all-plastic footwear such as wellingtons
P.V.C.	1.3	Polyvinylchloride

Range freestock	9.5.5	Part of the total freestock enabling one to restrict the size-mix
Rejects	2.5.4	Defective output
Resource planning	2.6	See supplement on planning terms
Safety stock	5.5	The planned level of saleable stock - a cover against stock-outs
Safety stock problem	5.7.3.1	Determination of suitable levels for the safety stocks
Saleable stock	2.2.1	Stock that can be sold before any size runs out
Sales budget	4.2.1	Part of the Management Plan (q.v.) dealing with sales
Sales cover	4.3.2	The number of weeks' demand which the current stock, of a size or brand, will satisfy
Sales forecasting	2.6	Forecasting the future demand
Sales group	Table 2	Group of related styles
Satisficing	3.2.3	Acceptance of any solution which satisfies specified minimum requirements
Scheduling requirements	9.2	Expected cumulative demand plus safety stocks
Screw clean	2.4.6	Cleaning the barrel prior to running a lighter colour
Seconds	2.5.4	Second quality output
Shoe	2.3	Footwear with a canvas 'upper' and plastic sole



Shortage costs	4.4	Costs associated with actual or potential stockouts
Shot size	8.2.1	The quantity of P.V.C. held in the injection barrel
Side mould	Diagram 3	Part of a mould forming the leg
Size	-	Shoe size, e.g. Juvenile's 12
Size freestock	9.5.5	Part of the total freestock which permits batch production from each mould
Size-mix cost	8.3.2	Cost associated with running a wide range of sizes together
Size range	Table 2	A group of shoe sizes, e.g. Womens
Sizeroll	2.2	Sales of one size per thousand sold of that brand
Sole plate	Diagram 3	Part of a mould forming the sole
(s,S)	7.2	Notation for a type of scheduling policy. Production starts when stocks fall to s, and stops when they reach S
Standard deviation	8.7.8.1	A measure of the variation in a variable. (The root-mean square)
Standard error	13.1	A measure of the variation in a forecast
Stationary demand	11.4.3	Demand whose pattern does not change with time, e.g. non-seasonal
Stochastic	11.2	Variable and unknown (usually of demand)

Stockout	-	Inability to meet demand
Style	Table 2	A style of footwear - includes brands of different colours
Template	2.4.2	A mould in its normal sense (see also mould)
Time series analysis	13.3	The analysis of ordered data looking for patterns
Trigger stock	11.5.3.4	Stock level at which production should commence
Unbalanced stock	2.2.1	The total stock minus the saleable stock
Upper	2.5.1	The top part of a canvas or leather shoe

## Supplement on planning terms

### Level 1

Production planning	All aspects of planning from sales forecasting to production scheduling
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### Level 2

Sales forecasting	Forecasting the future demand
Resource planning	Determining and requesting the necessary resources
Production scheduling	Scheduling the production to meet the demand using the available resources

### Level 3

Machine loading	Determining an aggregate (machine) schedule
Product scheduling	Making a detailed product schedule

### Level 4

Setting the safety stocks	Determining the appropriate safety stocks
Mould scheduling	Calculating the optimal batch quantities and hence the mould and product schedules.

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